PROPERTIES OF SELF-COMPACTING CONCRETE CONTAINING FLY ASH AND SILICA FUME

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Submitted by

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CERTIFICATE

This is to certify that the work presented in Thesis entitled "**Properties of self-compacting concrete containing fly ash and silica fume**" submitted by **Nitish Chalhotra, Roll No. 800922007** in partial fulfilment of the requirements for the award of **Master of Engineering in Civil (Structures) at Thapar University, Patiala**, is an authentic record of student's own work carried out under our supervision and guidance. The embodied in this thesis has not been submitted anywhere for award of any other degree.

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ABSTRACT

A self-compacting concrete (SCC) is the one that can be placed in the form and can go through obstructions by its own weight and without the need of vibration. Since its first development in Japan in 1988, SCC has gained wider acceptance in Japan, Europe and USA due to its inherent distinct advantages. The major advantage of this method is that SCC technology offers the opportunity to minimize or eliminate concrete placement problems in difficult conditions. It avoids having to repeat the same kind of quality control test on concrete, which consumes both time and labour. Construction and placing becomes faster & easier. It eliminates the need for vibration & reducing the noise pollution. It improves the filling capacity of highly congested structural members. SCC provides better quality especially in the members having reinforcement congestion or decreasing the permeability and improving durability of concrete.

The primary aim of this study is to explore the feasibility of using SCC by examining its basic properties and durability characteristics i.e. water absorption, shrinkage, sorptivity and sulfate resistance. An extensive literature survey was conducted to explore the present state of knowledge on the durability performance of self-consolidating concrete. However, because it usually requires a larger content of binder and chemical admixtures compared to ordinary concrete, its material cost is generally 20–50% higher, which has been a major hindrance to a wider implementation of its use. There is growing evidence that incorporating high volumes of mineral admixtures and microfillers as partial replacement for portland cement in SCC can make it cost effective. However, the durability of such SCC needs to be proven.

This research consists of: (i) development of a suitable mix for SCC that would satisfy the requirements of the plastic state; (ii) casting of concrete samples and testing them for compressive strength, shrinkage, water absorption, sulfate resistance and sorptivity. Local aggregates, cement, admixtures and additives produced by the local suppliers were used by in this work. The significance of this work lies in its attempt to provide some performance data of SCC so as to draw attention to the possible use of SCC.

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND OF SELF-COMPACTING CONCRETE

Cement-based materials are the most abundant of all man-made materials and are among the most important construction materials, and it is most likely that they will continue to have the same importance in the future. However, these construction and engineering materials must meet new and higher demands. When facing issues of productivity, economy, quality and environment, they have to compete with other construction materials such as plastic, steel and wood. One direction in this evolution is towards self-compacting concrete (SCC), a modified product that, without additional compaction energy, flows and consolidates under the influence of its own weight. The use of SCC offers a more industrialised production. Not only will it reduce the unhealthy tasks for workers, it can also reduces the technical costs of in situ cast concrete constructions, due to improved casting cycle, quality, durability, surface finish and reliability of concrete structures and eliminating some of the potential for human error. However, SCC is a sensitive mix, strongly dependent on the composition and the characteristics of its constituents. It has to possess the incompatible properties of high flow ability together with high segregation resistance. This balance is made possible by the dispersing effect of high-range water-reducing admixture (superplasticizer) combined with cohesiveness produced by a high concentration of fine particles in additional filler material.

The main mechanisms controlling this fine balance are related to surface physics and chemistry hence, SCC is strongly dependent on the activity of the admixtures, as well as on the large surface area generated by the high content of fines. Fresh SCC, like all cementitious materials, is a concentrated particle suspension with a wide range of particle sizes (from 10^{-7} to 30 mm for concrete). The particles are affected by a complex balance of inter-particle forces (i.e. interlocking, frictional, colloidal, and electrostatic forces), generating a time dependence and visco-plastic non-Newtonian behaviour. Self-compacting concrete is considered a concrete that can be placed and compacted under its own weight without any vibration effort, assuring complete filling of formworks even when access is hindered by narrow gaps between reinforcement bars. Concrete that must not be vibrated is a challenge to the building industry. In order to achieve such behaviour, the fresh concrete must show both high fluidity and good cohesiveness at the same time.

Self-compacting concrete (SCC) represents one of the most significant advances in concrete technology for decades. Inadequate homogeneity of the cast concrete due to poor compaction or segregation may drastically lower the performance of mature concrete in-situ. SCC has been developed to ensure adequate compaction and facilitate placement of concrete in structures with congested reinforcement and in restricted areas. SCC was developed first in Japan in the late 1980s to be mainly used for highly congested reinforced structures in seismic regions (Bouzoubaa, Lachemi, 2001). As the durability of concrete structures became an important issue in Japan, an adequate compaction by skilled labours was required to obtain durable concrete structures. This requirement led to the development of SCC and its development was first reported in 1989 (Okamura, Ouchi, 1999). SCC can be described as a high performance material which flows under its own weight without requiring vibrators to achieve consolidation by complete filling of formworks even when access is hindered by narrow gaps between reinforcement bars (Zhu et al., 2001). SCC can also be used in situations where it is difficult or impossible to use mechanical compaction for fresh concrete, such as underwater concreting, cast in-situ pile foundations, machine bases and columns or walls with congested reinforcement. The high flow ability of SCC makes it possible to fill the formwork without vibration (Khayat et al., 2004). Since its inception, it has been widely used in large construction in Japan (Okamura, Ouchi, 2003). Recently, this concrete has gained wide use in many countries for different applications and structural configurations (Bouzoubaa, Lachemi, 2001). It can also be regarded as "the most revolutionary development in concrete construction for several decades". Originally developed to offset a growing shortage of skilled labour, it is now taken up with enthusiasm across European countries for both site and precast concrete work.

It has proved beneficial economically because of a number of factors as noted below (Krieg, 2003 and ENFARC, 2002):

- Faster construction,
- Reduction in site manpower,
- Easier placing,
- Uniform and complete consolidation,
- Better surface finishes,
- Improved durability,
- Increased bond strength,
- Greater freedom in design,

- Reduced noise levels, due to absence of vibration, and
- Safe working environment.

The method for achieving self-compactability involves not only high deformability of paste or mortar, but also resistance to segregation between coarse aggregate and mortar when the concrete flows through the confined zone of reinforcing bars (Okamura, Ouchi, 2003). Homogeneity of SCC is its ability to remain unsegregated during transport and placing. High flowability and high segregation resistance of SCC are obtained by:

- A larger quantity of fine particles, i.e., a limited coarse aggregate content.
- A low water/powder ratio, (powder is defined as cement plus the filler such as fly ash, silica fume etc.) and
- The use of superplasticizer (Okamura, Ouchi, 2003 and Audenaert et al., 2002).

Because of the addition of a high quantity of fine particles, the internal material structure of SCC shows some resemblance with high performance concrete having self-compactability in fresh stage, no initial defects in early stage and protection against external factors after hardening. Due to the lower content of coarse aggregate, however, there is some concern that:

- SCC may have a lower modulus of elasticity, which may affect deformation characteristics of prestressed concrete members.
- Creep and shrinkage will be higher, affecting prestress loss and long-term deflection (Mata, 2004). Self-compacting concrete can be produced using standard cements and additives. It consists mainly of cement, coarse and fine aggregates, and filler, such as fly ash or Super-pozz, water, super plasticizer and stabilizer.

The composition of SCC is similar to that of normal concrete but to attain self flow ability admixtures, such as fly ash, glass filler, limestone powder, silica fume, Super-pozz, etc, with some superplasticizer is mixed. Since Super-pozz is a new emerging admixture and is a highly reactive alumino–silicate pozzolanic material, its fineness and spherical particle shape improves the workability of SCC. Thus, it can be used as a suitable admixture in SCC.

Three basic characteristics that are required to obtain SCC are high deformability, restrained flowability and a high resistance to segregation (Khayat, et al., 2004). High deformability is related to the capacity of the concrete to deform and spread freely in order to fill all the space in the formwork. It is usually a function of the form, size, and quantity of the aggregates, and the friction between the solid particles, which can be reduced by adding a high range water-reducing admixture (HRWR) to the mixture. Restrained flowability represents how easily the concrete can flow around obstacles, such as reinforcement, and is related to the member geometry and the shape of the formwork. Segregation is usually related to the cohesiveness of the fresh concrete, which can be enhanced by adding a viscosity-modifying admixture (VMA) along with a HRWR, by reducing the free-water content, by increasing the volume of paste, or by some combination of these constituents. Two general types of SCC can be obtained: (1) one with a small reduction in the coarse aggregates, containing a VMA, and (2) one with a significant reduction in the coarse aggregates without any VMA.

To produce SCC, the major work involves designing an appropriate mix proportion and evaluating the properties of the concrete thus obtained. In practice, SCC in its fresh state shows high fluidity, self-compacting ability and segregation resistance, all of which contribute to reducing the risk of honey combing of concrete (Su et al., 2001).With these good properties, the SCC produced can greatly improve the reliability and durability of the reinforced concrete structures. In addition, SCC shows good performance in compression and can fulfil other construction needs because its production has taken into consideration the requirements in the structural design.

1.2 NEED FOR THIS RESEARCH

Despite its advantages as described in previous section, SCC has not gained much local acceptance though it has been promoted in the Middle East for the last five years. The majority of applications thus far have been small niche pours into congested areas, domes, or thin wall sections. In UAE, specifically in Dubai, there are a few high-rise structures under construction using SCC and many more are expected in future (Kapoor et al., 2003).

Awareness of SCC has spread across the world, prompted by concerns with poor consolidation and durability in case of conventionally vibrated normal concrete. However, the awareness in the Kingdom of Saudi Arabia regarding SCC is somewhat muted and this explains the lack of any commercial use of SCC in the Kingdom thus far. The reluctance in utilizing the advantages of SCC, if any, in Saudi Arabia, stems from two contributing factors:

- Lack of research or published data pertaining to locally produced SCC, and
- The potential problems for the production of SCC, if any, with local marginal aggregates and the harsh environmental conditions prevailing in the region. Locally available aggregates are characterized as porous, absorptive, relatively soft,

excessively dusty, and the coefficient of thermal expansion is much less than that of the hardened cement mortar. The climate of this region is characterized by high temperature and humidity with large fluctuations in the diurnal and seasonal temperature and humidity. Therefore, there is a need to conduct studies on SCC using local aggregates.

Self-compacting concrete (SCC) is a sensitive mix, strongly dependent on the composition and the characteristics of its constituents. It has to possess the incompatible properties of high flow ability together with high segregation resistance, a balance made possible by the dispersing effect of water-reducing admixture combined with cohesiveness produced by a high concentration of fine particles. The motive for development of self-compacting concrete was the social problem on durability of concrete structures that arose around 1983 in Japan. Due to a gradual reduction in the number of skilled workers in Japan's construction industry, a similar reduction in the quality of construction work took place. As a result of this fact, one solution for the achievement of durable concrete structures independent of the quality of construction work was the employment of self-compacting concrete, which could be compacted into every corner of a formwork, purely by means of its own weight.

1.3 CONSTRUCTION ISSUES

By employing self-compacting concrete, the cost of chemical and mineral admixtures is compensated by the elimination of vibrating compaction and work done to level the surface of the normal concrete (Khayat et al., 1997). 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. SCC can greatly improve construction systems previously based on conventional concrete requiring 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. The main reasons for the employment of self-compacting concrete can be summarized as follows:

- To shorten construction period.
- To assure compaction in the structure - especially in confined zones where vibrating compaction is difficult.

- To eliminate noise due to vibration - effective especially at concrete products plants.

The method for achieving self-compactability involves not only high deformability of paste or mortar, but also resistance to segregation between coarse aggregate and mortar when the concrete flows through the confined zone reinforcing bars.

Okamura, Ozawa (2003) have employed the following methods to achieve self-compactability:

- Limited aggregate content
- Low water-powder ratio
- Use of super plasticizer

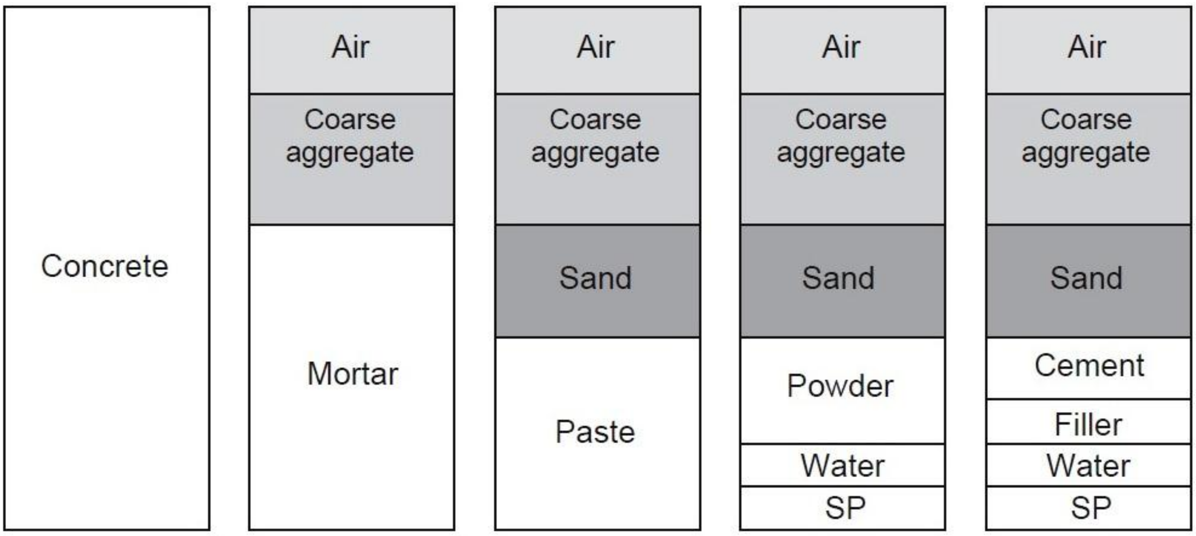

Fig 1.1: The schematic composition of SCC (Brouwers, Radix, 2005)

The frequency of collision and contact between aggregate particles can increase as the relative distance between the particles decreases and then internal stress can increase when concrete is deformed, particularly near obstacles. Research has found that the energy required for flowing is consumed by the increased internal stress, resulting in blockage of aggregate particles. Limiting the coarse aggregate content, whose energy consumption is particularly intense, to a level lower than normal is effective in avoiding this kind of blockage. Highly viscous paste is also required to avoid the blockage of coarse aggregate when the concrete flows through obstacles. When the concrete is deformed, paste with a high viscosity also prevents localized increases in internal stress due the approach of coarse aggregate particles. High deformability can be achieved only by the employment of a superplasticizer, keeping the water-powder ratio to a very low value.

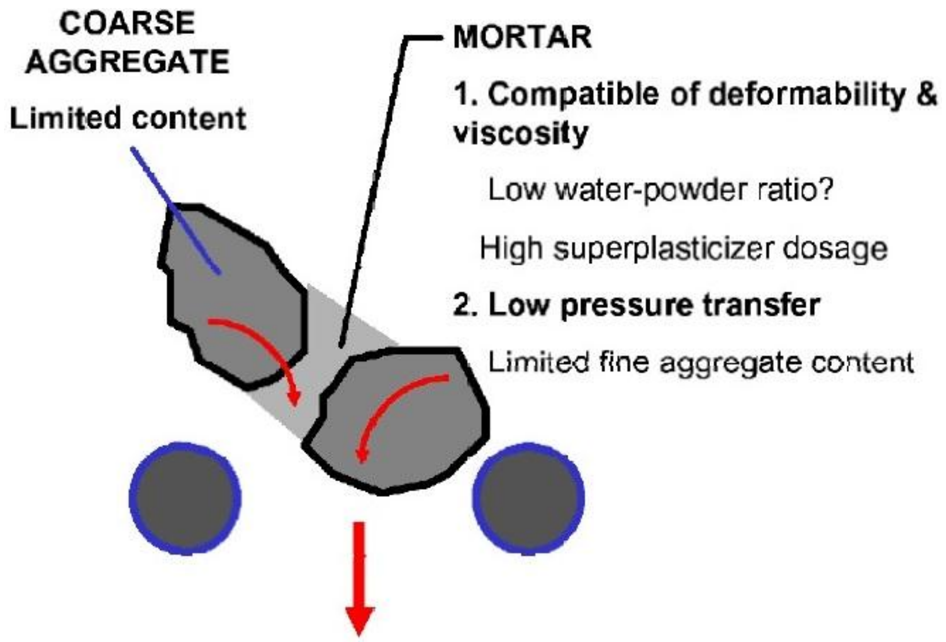

Fig 1.2: Mechanism for achieving self-compactability (Okamura, Ouchi, 2003)

1.3.1 SCC PRODUCTION

- Production of SCC requires more experience and care than the conventional vibrated concrete. The plant personnel would need training and experience to successfully produce and handle SCC. In the beginning, it may be necessary to carry out more tests than usual to learn how to handle SCC and gain the experience.
- Before any SCC is produced at the plant and used at the job site, the mix must be properly designed and tested to assure compliance with the project specifications. The ingredients and the equipment used in developing the mix and testing should be the same ingredients and equipment to be used in the final mix for the project.
- Most common concrete mixers can be used for producing SCC. However, the mixing time may be longer than that for the conventional vibrated concrete. SCC is more sensitive to the total water content in the mix. It is necessary to

take into account the moisture/water content in the aggregates and the admixtures before adding the remaining water in the mix. The mixer must be clean and moist, and contains no free water.

- Admixtures for the SCC may be added at the plant or at the site. There is cost benefit in adding the admixtures at the site. Conventional ready-mix concrete can be bought at a lower cost than the cost of SCC bought from a ready-mix supplier.

1.3.2 TRANSPORTATION

- The truck drivers should be given oral and written instructions for handling SCC. The truck drivers must check the concrete drum before filling with SCC to make sure that the drum is clean and moist, but with no free water. Extra care must be taken for long deliveries. In addition to the usual information, the delivery note should show the following information:
  1) Slump flow - target value and acceptable range.
  2) Production time - time when it was produced.
  3) Instruction for adding admixtures at the site, if allowed.
- The truck drivers should not be allowed to add water and/or admixtures during transit.

1.3.3 FORM SYSTEM

- All commonly used form materials are suitable for SCC. For surface quality of SCC, wood is better than plywood, and plywood is better than steel. More pores seem to form on the surface when the form skin is colder than the SCC. During cold weather placement of SCC, it may be necessary to insulate the formwork to maintain temperature and normal setting time. SCC is more sensitive to temperature during the hardening process than the conventional vibrated concrete.
- Due to the cohesiveness of SCC, the formwork does not need to be tighter than that for conventional vibrated concrete.
- Higher form pressures than normal were not observed even at high rate of concrete placement. However, it is recommended that the formwork be designed for hydrostatic pressure, unless testing has shown otherwise.

1.3.4 CASTING ON SITE

- A pre-SCC placement meeting with all personnel involved in the SCC placement would be beneficial. The SCC placement plan, including QC/QA, and the roles and responsibilities of the field personnel should be explained and understood.
- In addition to the normal testing, the slump flow, T50 and L-box tests are useful to check SCC at the job site before placement.
- SCC can flow horizontally a distance of 15 to 20m without segregation. A well-designed SCC may have a free fall of as much as 8m without segregation. However, it is recommended that the distance of horizontal flow be limited to 10m and the vertical free fall distance be limited to 5m.
- For deck slab of a bridge, it would be difficult for the SCC to flow too far. This could be handled by designing SCC with a lower slump flow. With a lower slump flow, a bridge deck with a slope of 2% could also be accomplished.
- If an SCC placement is interrupted and the concrete has started to harden, it would be necessary to wake up the placed concrete by striking a stick or board into the concrete several times before starting the placement again.
- SCC takes some time before the hardening starts, especially during cold weather conditions. When it starts to harden, the process is very rapid, which can cause problems in levelling and treating large surface areas.

1.3.5 SURFACE FINISHING AND CURING

- Finishing and curing of SCC can follow the good practices of superplasticized high performance concrete. Surface of SCC should be roughly levelled to the specified dimensions, and the final finishing applied as necessary before the concrete hardens.
- SCC tends to dry faster than conventional vibrated concrete, because there is little or no bleeding water at the surface. SCC should be cured as soon as practicable after placement to prevent surface shrinkage cracking.

1.3.6 COLD JOINT

- When placing a new layer of SCC on old SCC, the bond between the old and new SCC is equal to or better than in the case of conventional vibrated concrete. Normal vibration will not destroy the concrete, such as in the case of placing conventional vibrated concrete on fresh SCC. This may be necessary when the surface slope is greater than practicable for SCC.

1.4 INTERNATIONAL STATUS

Self-compacting concrete has already been used in several countries. In Japan, major construction projects included the use of SCC in the late ’90s. Today, in Japan, efforts are being made to free SCC of the “special concrete” label and integrate it into day-to-day concrete industry production (Okamura, 1997). Currently, the percentage of self-compacting concrete in annual product of ready-mixed concrete (RMC), as well as precast concrete (PC), in Japan is around 1.2% and 0.5% of concrete products. In the United States, the precast industry is also leading SCC technology implementation through the precast/pre-stressed Concrete Institute (PCI) which has done some research on the use of SCC in precast/pre-stressed concretes starting with 1999. It is estimated that the daily production of SCC in the precast/pre-stressed industry in the United States will be 8000 m^3 in the first quarter of 2003 (around 1% of the annual ready-mix concrete).

Furthermore, several state departments of transportation in the United States (23 according to a recent survey) (Bartos, 2000) are already involved in the study of SCC. With such a high level of interest from the construction industry, as well as manufacturers of this new concrete, the use of SCC should grow at a tremendous rate in the next few years in the United States. However, even if it is made from the same constituents the industry has used for years, the whole process, from mix design to placing practices, including quality control procedures, needs to be reviewed and adapted in order for this new technology to be applied properly. Research regarding the self-compacting concrete was also carried out in Canada, few years after the concept was introduced in Japan. Institute for Research in Construction, Canadian precast/pre-stressed Concrete Institute, CONMET-ICON, and ISIS are some of the bodies which studied various aspects of the new technology. The introduction of the SCC in Europe is largely connected with the activities of the international association RILEM, France, particularly of its Technical Committee TC145-WSM on “Workability of Fresh Special

Concrete Mixes" (Dhir, Dyer, 1999). The TC145-WSM was founded in 1992 and immediately attracted expert memberships from all over the world. The aim was to look at the production stage of a number of "special" concretes and identify workability parameters and other characteristics of the mixes in their fresh state that governed the reliable and economical achievement of the "special" or "high-performance" parameters the concretes offered. As the importance of the SCC became widely recognized, other European countries, Germany, Sweden, UK, Denmark, Netherlands, Norway, Finland, etc., have decided to keep up with the developments in this area. For example, in Sweden, the SCC market share was at five percent in RMC and PC in 2002, and was expected to double in 2003. Housing and tunnelling, as well as bridge construction for the Swedish National Road Administration were the main areas of use for SCC. In the Netherlands and Germany, the precast industry is mainly driving the development of SCC, with an expected eight percent of market share in 2003 in Netherlands. Today, self-compacting concrete is being studied worldwide, with papers presented at almost every concrete-related conference, but until now there is no universally adopted standardized test method for evaluation of self-compatibility of this concrete.

Currently, the use of self-compacting concrete is being rapidly adopted in many countries. The use of self-compacting concrete should overcome concrete placement problems associated with the concrete construction industry. However, there still is a need for conducting more research and development work for the measurement and standardization of the methods for the evaluation of the self-compacting characteristics of SCC.

1.5 APPLICATIONS OF SELF-COMPACTING CONCRETE

Compared to normally vibrated concrete (NVC), self-compacting concrete (SCC) possesses enhanced qualities and improves productivity and working conditions due to the elimination of compaction. SCC generally has higher powder content than NVC and thus it is necessary to replace some of the cement by additions to achieve an economical and durable concrete. Japan has used self-compacting concrete (SCC) in bridge, building and tunnel construction since the early 1990's. In the last five years, a number of SCC bridges have been constructed in Europe. In the United States, the application of SCC in highway bridge construction is very limited at this time. However, the U.S. precast concrete industry is beginning to apply the technology to architectural concrete. SCC has high potential for wider structural applications in highway bridge construction.

The application of concrete without vibration in highway bridge construction is not new. For examples, placement of concrete underwater has been placed without vibration, and shaft concrete can be successfully placed without vibration. These seal, mass and shaft concretes are generally of lower strength, less than 34.5 MPa and difficult to attain consistent quality. Modern application of self-compacting concrete (SCC) is focused on high performance. Better and more reliable quality, dense and uniform surface texture, improved durability, high strength, and faster construction. Recognizing the lack of uniformity and complete compaction of concrete by vibration, researchers at the University of Tokyo, Japan, started out in late 1980's to develop SCC. By the early 1990's Japan has developed and used SCC that does not require vibration to achieve full compaction. More and more applications of SCC in construction have been reported in Japan as shown in Fig 1.3. As of the year 2000, the amount of SCC used for prefabricated products (precast members) and ready-mixed concrete (cast-in-place) in Japan was about 400,000 m^3.

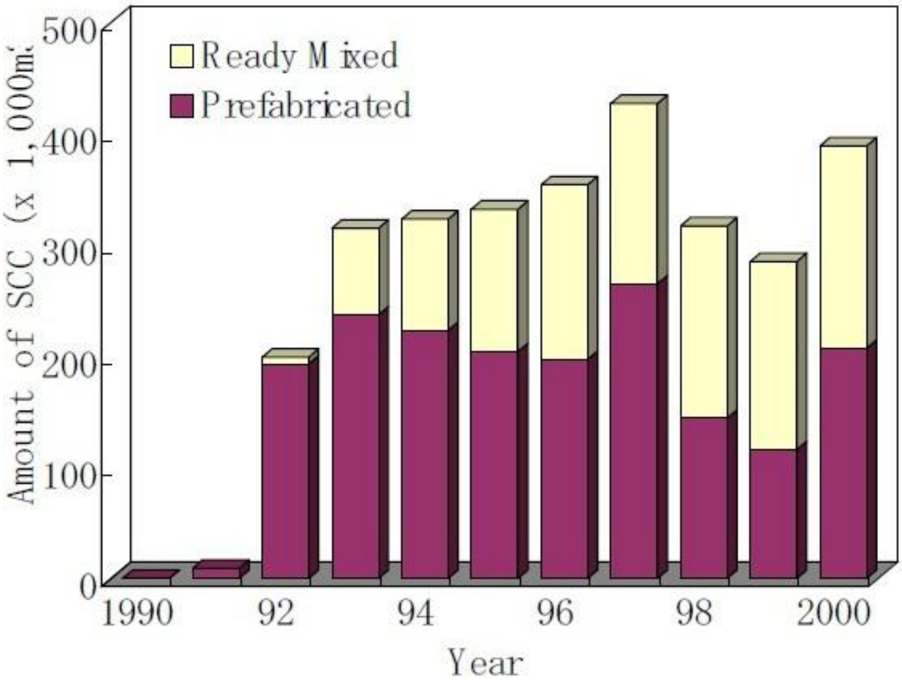

Fig 1.3: Amount of SCC Placement in Japan (Ouchi et al. 2003)

Several European countries were interested in exploring the significance and potentials of SCC developed in Japan. These European countries formed a large consortium in 1996 to embark on a project aimed at developing SCC for practical applications in Europe. The title of the project is Rational Production and Improved Working Environment through using Self-compacting Concrete. In the last six years, a number of SCC bridges, walls and tunnel linings have been constructed in Europe. In the United States, SCC is beginning to gain interest, especially by the precast concrete industry and admixture manufacturers. The precast concrete industry is beginning to apply the technology to commercial projects when specifications permit. The applications range from architectural concrete to complex private bridges.

1.6 ADVANTAGES AND DISADVANTAGES

SCC offers many advantages for the precast, pre-stressed concrete industry and for cast-insitu construction:

- Low noise-level in the plants and construction sites.
- Eliminated problems associated with vibration.
- Less labour involved.
- Faster construction.
- Improved quality and durability.
- Higher strength.
- SCC can be placed at a faster rate with no mechanical vibration and less screeding, resulting in savings in placement costs.
- Improved and more uniform architectural surface finish with little to no remedial surface work.
- Ease of filling restricted sections and hard-to-reach areas. Opportunities to create structural and architectural shapes and surface finishes not achievable with conventional concrete.
- Improved consolidation around reinforcement and bond with reinforcement.
- Improved pumpability.
- Improved uniformity of in-place concrete by eliminating variable operator-related effort of consolidation.
- Labour savings.
- Shorter construction periods and resulting cost savings.

- Quicker concrete truck turn-around times, enabling the producer to service the project more efficiently.
- Reduction or elimination of vibrator noise, potentially increasing construction hours in urban areas.
- Minimizes movement of ready mixed trucks and pumps during placement.
- Increased jobsite safety by eliminating the need for consolidation.

Disadvantage of Self-compacting Concrete,

- Although the use of SCC has many technical, social, and overall economical advantages, its supply cost is two to three times higher than that of normal concrete depending upon the composition of the mixture and quality control of concrete producer. Such a high premium has somehow limited SCC application to general construction. SCC is specified only to areas where it is most needed. These include places where access to conventional vibration is difficult, or where there are congested reinforcements.
- The major difficulty which was faced in development of SCC was on account of contradictory factors that the concrete should be fully flow able but without bleeding or segregation. It is required that the cement mortar of the SCC should have higher viscosity to ensure flow ability while maintaining non–sedimentation of bigger aggregates.
- Drawbacks of Okamura's method are that (i) it requires quality control of paste and mortar prior to SCC mixing, while many ready-mixed concrete producers do not have the necessary facilities for conducting such tests and (ii) the mix design method and procedures are too complicated for practical implementation.

1.7 SUPPLYMENTRY CEMENTING MATERIALS

Supplementary cementing materials (SCM), also called mineral admixtures, contribute to the properties of hardened concrete through hydraulic or pozzolanic activity. Typical examples are natural pozzolans, fly ash, ground granulated blast-furnace slag and silica fume which can be used individually with portland or blended cement or in different combinations. These materials react chemically with calcium hydroxide released from the hydration of portland cement to form cement compounds. These materials are often added to concrete to make concrete mixtures more economical, reduce permeability, increase strength, or influence other concrete properties. Early SCMs consisted of natural, readily available materials such as volcanic ash or diatomaceous earth. More recently, strict air-pollution controls and regulations have produced an abundance of industrial by products that can be used as supplementary cementitious materials such as fly ash, silica fume and blast furnace slag. The use of such by products in concrete construction not only prevents these products from being land-filled but also enhances the properties of concrete in the fresh and hydrated states. SCMs can be used either as an addition to the cement or as a replacement for a portion of the cement. Most often SCM will be used to replace a portion of the cement content for economical or property-enhancement reasons. Supplementary cementitious materials are often incorporated in the concrete mix to reduce cement contents, improve workability, increase strength and enhance durability.

SCMs can be divided into two categories based on their type of reaction Supplementary cementing material or mineral admixture are generally the by- products of other industries and are relatively cheaper than chemical admixtures. Hence have a potential to reduce the cost of concrete in addition to conferring the benefit of providing supplementary cementitious properties. These admixtures play a reactive part in chemical reactions of the hydration system. Mineral admixture include for e.g. Silica fume (micro-silica), Fly ash, rice husk, GGBFS, Natural Pozzolons etc.

Table 1.1: Classification of Mineral Admixtures (Lothia, Joshi, 1996)

Classification	**Chemical and mineralogical Composition**	**Particle Characteristics**
Highly Active Pozzolans • *Condensed SF*	*Consists essentially of pure silica in no crystalline form.*	*Extremely fine powder consisting of solids spheres of 0.1 micrometer average diameter (about 20 $m^{2/}$g surface area by nitrogen absorption).*
• *Rice Husk Ash:*	*Consist essentially of pure silica in noncrytalline form.*	*Particles are generally less than 45 micrometer but they are highly cellular (about 60m^2/g surface area by nitrogen absorption).*
Normal Pozzolans • *Low-calcium Fly Ash*	*Mostly silicate glass containing aluminium, iron, and alkalis. The small quantity of crystalline matter present consist generally of quartz, mullite, sillimanite, heatic magnetic.*	*Powder corresponding to 15-30% particle larger than 45 micrometer (usually 200-300 m^2 /kg blain).most particles are solid spheres of average 20 micrometer diameter .cenospheres and plerospheres may be present.*
• *Natural Material*	*Besides aluminosilicate glass, natural pozzolans contain quartz feldser,mica.*	*Particles are ground to mostly under 45 micrometer and have rough texture.*
Weak Pozzolans *Slowly-cooled blast furnace slag, bottom ash, field burnt rice husk ash.*	*Consists essentially of crystalline silicate minerals,and only a small amount of no crystalline matter*	*The material must be pulverized to very fine particle size in order to develop some pozzolonic activity. Ground particles are rough in texture.*

1.7.1 FLY ASH

Fly ash (FA) is a by-product of the combustion of pulverized coal in thermal power plants. It is removed by the dust collection systems from the exhaust gases of fossil fuel power plants as very fine, predominantly spherical glassy particles from the combustion gases before they are discharged into atmosphere. The size of particles is largely dependent on the type of dust collection equipment. Diameter of fly ash particles ranges from less than 1 µm–150 µm. It is generally finer than Portland cement. Their surface area is typically 300 to 500 m^2/kg, although some fly ashes can have surface areas as low as 200 m^2/kg and as high as 700 m^2/kg. Fly ash is primarily silicate glass containing silica, alumina, iron, and calcium. The relative density or specific gravity of fly ash generally ranges between 1.9 and 2.8 and the colour is generally gray or tans (Halstead, 1986). The chemical composition of fly ash is determined by the types and relative amounts of incombustible material in the coal used. The major chemical constituents in fly ash are silica, alumina and oxides of calcium and iron. Because of its fineness and pozzolanic and sometimes self-cementitious nature, fly ash is widely used in cement and concrete.

1.7.1.1 Classification of Fly Ash

ASTM – C 618-93 categorizes natural pozzolans and fly ashes into the following three categories:

- Class N Fly ash: Raw or calcined natural pozzolans such as some diatomaceous earths, opaline chert and shale, stuffs, volcanic ashes and pumice come in this category. Calcined kaolin clay and laterite shale also fall in this category of pozzolans.
- Class F Fly ash: Fly ash normally produced from burning anthracite or bituminous coal falls in this category. This class of fly ash exhibits pozzolanic property but rarely if any, self-hardening property.
- Class C Fly ash: Fly ash normally produced from lignite or sub- bituminous coal is the only material included in this category. This class of fly ash has both pozzolanic and varying degree of self cementitious properties. (Most class C fly ashes contain more than 15 % CaO. But some class C fly ashes may contain as little as 10 % CaO.

Table 1.2: Requirements for fly ash and natural pozzolans for use as a mineral admixture in Portland cement concrete as per ASTM C 618-93.

Requirements	Fly Ash Classification		
	N	**F**	**C**
Chemical Requirements			
SiO_2 + Al2O_3 + Fe_2O_3, min %	70	70	70
SO_3, max %	4	5	5
Moisture content, max %	3	3	3
Loss on ignition, max %	10	6	6
Physical Requirements			
Amount retained when wet sieved on 450 mm.Sieve, max %	34	34	34
Pozzolanic activity index, with Portland cement at 28 days, min % of control	75	75	75
Pozzolanic activity index, with lime, at 7 days,min (MPa)	5.5	5.5	-
Water requirement, max % of control	115	105	105
Autoclave expansion or contraction, max %	.8	.8	.8
Specific ravity, max variation from average.	5	5	5
Percentage retained on 45 sieve, max variation,and percentage points from average.	5	5	5

Table 1.3: Chemical Requirements

S. No.	Characteristics	Requirement (%)
1	Silicon dioxide (SiO_2) + aluminium oxide (Al_2O_3) + iron oxide (Fe2O3), percent by mass, Min.	70
2	Silicon dioxide (SiO_2), percent by mass, Min.	35
3	Magnesium oxide (MgO), percent by mass, Max.	5
4	Total sulphur as sulphur trioxide (SO_3), percent by mass,Max	2.75
5	Available alkalis as sodium oxide (Na_2O), percent by mass, Max.	1.5
6	Loss on Ignition, percent by mass, Max.	12
7	Moisture content, percent by mass	3

1.7.2 Silica Fume

Silicon, ferrosilicon and other silicon alloys are produced by reducing quartz, with coal and iron or other ores, at very high temperatures (2000°C) in electric arc furnaces (St. John, 1998). Some silicon gas or fume is produced in the process, which reaches the top of the furnace with other combustion gases, where it becomes oxidized to silica in contact with the air and then condenses as < 0.1 μm to 1 μm spherical particles of amorphous silica. This material is usually known as silica fume. It is also referred to as micro silica or more properly, condensed silica fume (csf). Silica fume is an ultra fine powder, with individual particle sizes between 50 and 100 times finer than cement, comprising solid spherical glassy particles of amorphous silica (85-96 percent SiO_2). However, the spherical particles are usually agglomerated so that the effective particle size is much coarser. Silica fume used in concrete derives from the manufacture of ferrosilicon alloys and is modified by densification, micropelletization or slurrification, to facilitate transportation and handling. Condensed silica fume has a surface area of about 20000 m^2/kg and a relative density generally in the range of 2.20 to 2.5 (Kosmatka et al., 2002).

The pozzolanic reactions take place when silica fume is added to the concrete mixture, and the amorphous silica, which is the major component of the pozzolana, reacts with calcium hydroxide formed from the hydration of the calcium silicates with the resulting product being a calcium silicate hydrate (C-S-H) (Mindess et al., 2003). Usually, after micro silica is being added to the concrete mix, the matrix of micro silica concrete becomes very dense (St John, 1998). This denseness effect has been attributed to the extreme fineness of micro silica, due to the fact that 50,000 to 100,000 microspheres exist for every cement grain, allowing micro silica hydration products to infill the water spaces usually left within the cement hydrates. Silica fume is used in amounts between 5% and 10% by mass of the total cementitious material, in applications where high degree of impermeability and high compressive strength are needed in concrete. In some situations, the water demand of concrete containing silica fume increases with increasing amounts of silica fume, unless a water reducer or plasticizer is used. Some lean mixes may not experience an increase in water demand when only a small amount (less than 5%) of silica fume is present.

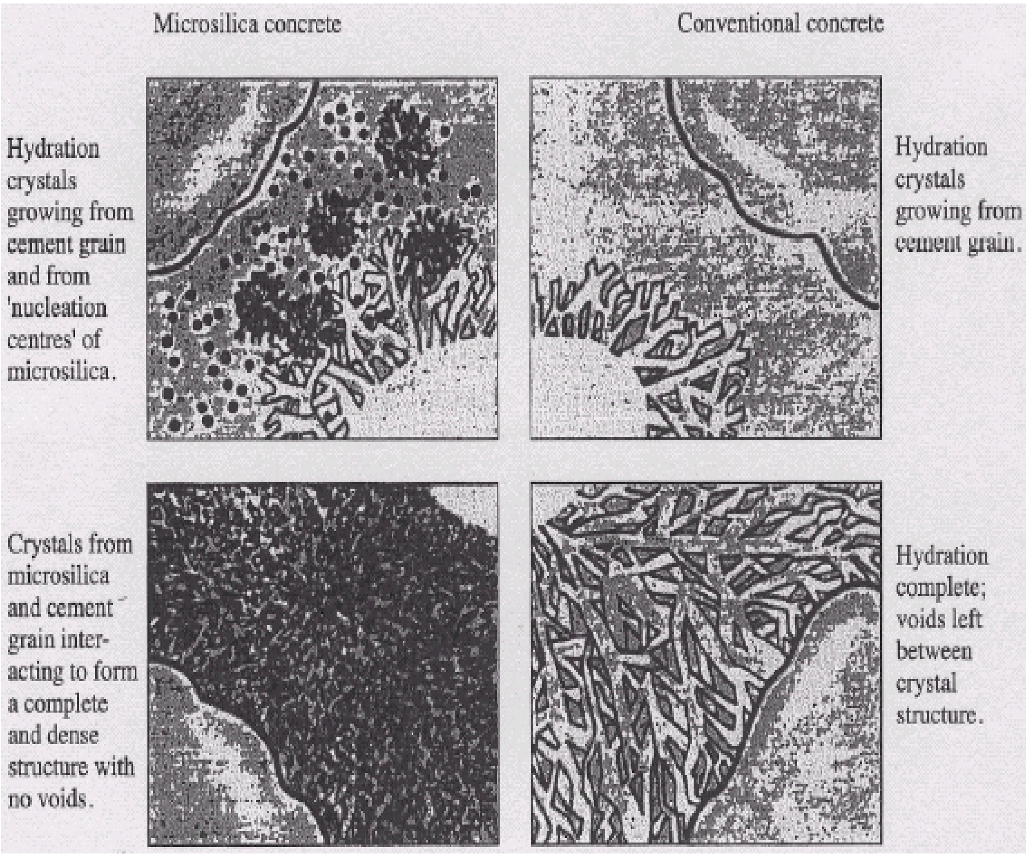

Fig 1.4: Effect of microsilica in densifying the concrete mix - comparison between conventional and microsilica concretes (St John, 1998).

Micro silica is also very effective in reducing both bleeding and segregation. It may contribute to stickiness of a concrete mixture, adjustments, including the use of high-range water reducers, may be required to maintain workability and permit proper compaction and finishing. With proper proportioning and material selection, silica fume can improve the durability of concrete, its resistance to sulphate attack and the early strength development (Ramachandran, 1984).

Table 1.4: Physical Properties of Silica Fume (Khayat, Aitcin, 1987)

Colour	**Varies from white or pale-grey to a dark grey**
Specific Gravity	It is generally equal to that amorphous silicon which is about 2.2. depending upon its chemical composition the specific gravity of silica fume particle can be as high as 2.4-2.55
Specific Surface Area	About 20000 m^2/kg approximately 10 times more than Portland cement
Particle Size	Mostly fine spheres with a mean diameter of .1 micron
Bulk Loose Density	230-300kg/m^3

Table1.5: Chemical composition of Silica Fume (Khayat, Aitcin, 1987)

Constituents	Percent
SiO_2	90-96
Al_2O_3	0.5-0.8
MgO	0.5-1.5
Fe_2O_3	0.2-0.8
CaO	0.1-0.5
Na_2O	0.2-0.7
K_2O	0.4-1.0
C	0.5-1.4
S	0.1-0.4

CHAPTER 2: LITERATURE REVIEW

2.1 GENERAL

In this chapter the research work concerning to the various application and methods used for testing of the Self-compacting Concrete made by various cementitious materials and admixtures are discussed. This chapter gives a comprehensive review of the work carried out by various researchers in the field of Self-compacting Concrete.

2.2 FRESH CONCRETE PROPERTIES

2.2.1 Workability

EFNARC (2002) investigated that the SCC flows alone under its dead weight up to levelling, airs out and consolidates itself thereby without any entry of additional compaction energy and without a nameable segregation. Due to the high content of powder, SCC may show more plastic shrinkage or creep than ordinary concrete mixes. These aspects should therefore be considered during designing and specifying SCC. Current knowledge of these aspects is limited and this is an area requiring further research.

A concrete mix can only be classified as Self-compacting Concrete if the requirements for all three characteristics are fulfilled.

- Filling Ability: Ability of to fill a formwork completely under its own weight.
- Passing Ability: Ability to overcome obstacles under its own weight without hindrance. Obstacles are e.g. reinforcement and small openings etc.
- Segregation Resistance: Homogeneous composition of concrete during and after the process of transport and placing.

They were further elaborated as:

Table 2.1: List of test methods for workability properties of SCC (EFNARC, 2002)

	Method	Property
1	Slump-flow by Abrams cone	Filling ability
2	T_{50cm} slump flow	Filling ability
3	J-ring	Passing ability
4	V-funnel	Filling ability
5	V-funnel at $T_{5minutes}$	Segregation resistance
6	L-box	Passing ability
7	U-box	Passing ability
8	Fill-box	Passing ability
9	GTM screen stability test	Segregation resistance
10	Orimet	Filling ability

For the initial mix design of SCC all three workability parameters need to be assessed to ensure that all aspects are fulfilled. These requirements are to be fulfilled at the time of placing. Likely changes in workability during transport should be taken into account in production. Typical acceptance criteria for Self-compacting Concrete with a maximum aggregate size up to 20 mm are shown in Table 2.2.

Table 2.2: Acceptance criteria for Self-compacting Concrete (EFNARC, 2002)

	Method	Unit	Typical range of values	
			Minimum	**Maximum**
1	Slumpflow by Abrams cone	mm	650	800
2	T_{50cm} slumpflow	sec	2	5
3	J-ring	mm	0	10
4	V-ring	sec	6	12
5	Time increase, V-funnel at $T_{5minutes}$	sec	0	3
6	L-box	(h_2/h_1)	0.8	1
7	U-box	(h_2-h_1) mm	0	30
8	Fill-box	%	90	100
9	GTM Screen stability test	%	0	15
10	Orimet	sec	0	5

If a certain test result is out of range it can have different causes. The possible cause can be found with more certainty by checking the value to other test methods and subjectively checking the workability characteristics. In this way the best possible action for solving a problem can be found. Table 2.3 and Table 2.4 provide a list of possible actions and the effect that usually occurs in concrete. It is obvious that the effect depends upon the size of the action and on the actual workability and composition of the concrete mix. Every action can have both positive and negative effect on the different concrete characteristics.

If the test results between different batches or loads vary considerably, the cause can be the variation of:

- Cement characteristics
- Addition characteristics
- Grading of aggregates
- Moisture content of aggregates,
- Temperature

- Mixing procedure
- Time of testing

Table 2.3: Fault-finding for low results (EFNARC, 2002)

	Method	Unit	Result less than		Possible cause
1	Slumpflow by Abrams cone	mm	650	a	viscosity too high
				c	yield value too high
2	T_{50cm} slumpflow	sec	2	b	viscosity too low
3	J-ring	mm	10	a	viscosity too high
				c	yield value too high
				d	segregation
				f	blockage
4	V-funnel	sec	8	b	viscosity too low
5	Increase in V-funnel at T_{5min}	sec	0.8	g	doubtful result
6	L-box (h_2/h_1)			a	viscosity too high
				c	yield value too high
				f	blockage
7	U-box (h_2-h_1)	mm	0	g	false result
8	Fill-box	%	90	a	viscosity too high
				c	yield value too high
9	Screen stability test	%	5	a	viscosity too high
				f	blockage

Table 2.4: Fault-finding for high results (EFNARC, 2002)

	Method	Unit	Result more than		Possible cause
1	Slumpflow by Abrams cone	mm	750	b	viscosity too low
				d	segregation
2	T_{50cm} slumpflow	sec	5	a	viscosity too high
				c	yield value too high
3	J-ring	mm		b	viscosity too low
				d	segregation
4	V-funnel	sec	12	a	viscosity too high
				c	yield value too high
				f	blockage
5	Increase in V-funnel at T_{5min}	sec	3	d	segregation
				e	rapid loss in workability
				f	blockage
6	L-box (h_2/h_1)		1	g	false result
7	U-box (h_2-h_1)	mm	30	a	viscosity too high
				c	yield value too high
				f	blockage
8	Fill-box	%	100	g	false result
9	Screen stability test	%	15	d	segregation

Existing Tests for Fresh SCC Mixes:

U-type test: Of the many testing methods used for evaluating self-compactability, the U-type test (Fig 2.1) proposed by the Taisei group is the most appropriate, due to the small amount of concrete used, compared to others (Ferraris, 1999). In this test, the degree of compact ability can be indicated by the height that the concrete reaches after flowing through obstacles. Concrete with the filling height of over 300 mm can be judged as self-compacting. Some companies consider the concrete self-compacting if the filling height is more than 85% of the maximum height possible.

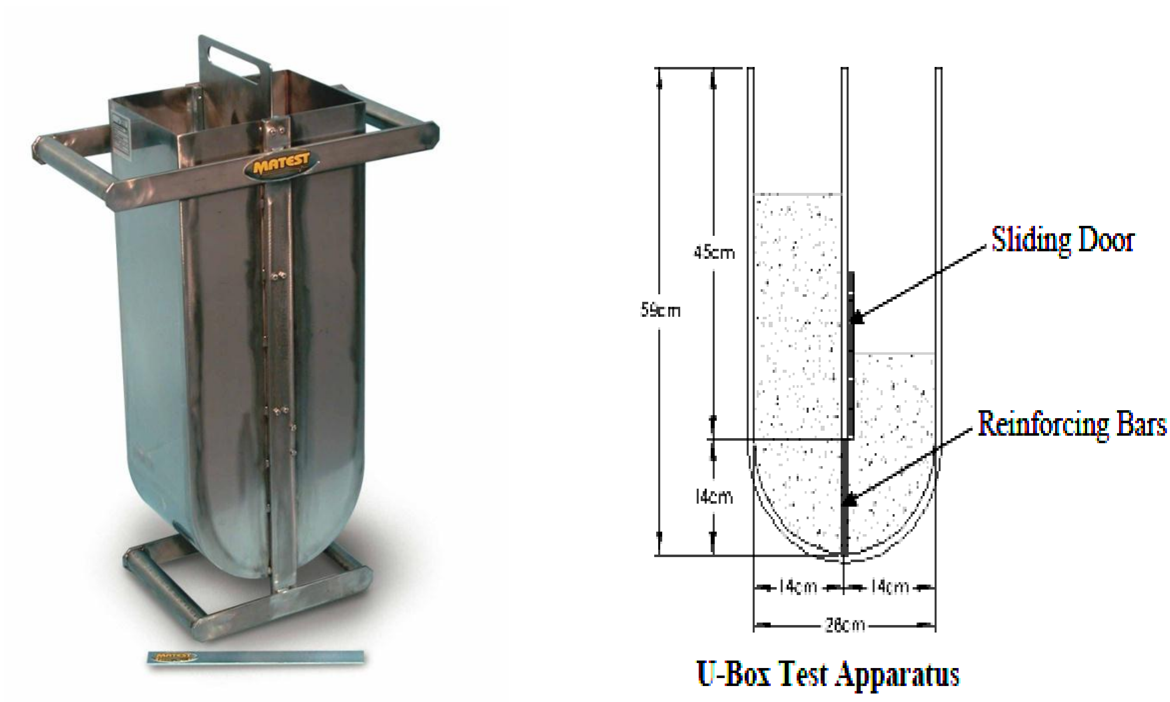

Fig 2.1: U-type test (Ferraris, 1999)

Slump Flow test: The basic equipment used is the same as for the conventional Slump test. The test method differs from the conventional one by the fact that the concrete sample placed into the mould is not rodded and when the slump cone is removed the sample collapses (Ferraris, 1999). The diameter of the spread of the sample is measured, i.e. a horizontal distance is determined as opposed to the vertical distance in the conventional Slump test. The

Slump Flow test can give an Indication as to the consistency, filling ability and workability of SCC. The SCC is assumed of having a good filling ability and consistency if the diameter of the spread reaches values between 650mm to 800mm.

Fig 2.2: Slump cone test (Ferraris, 1999)

L-box test: The L-box test evaluates the passing ability of SCC in a confined space. The L-box is composed of a vertical arm and a horizontal arm as shown in Fig 2.3. The concrete flows from the vertical arm, through reinforcing bars and into the horizontal arm of the box. A more detailed test procedure is in Fig. 2.3.

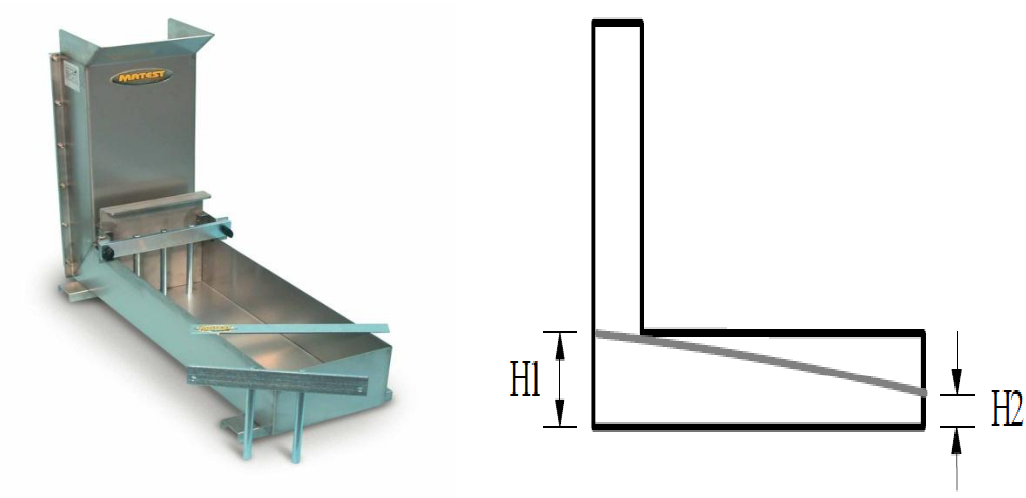

Fig 2.3: Schematic of L-box (Ferraris, 1999)

Once the test is completed, the ratio of the heights of the concrete at the two ends of the box, called the blocking ratio (BR), is used to evaluate the passing ability with obstructions as

$$BR = H2/H1$$

If the SCC has perfect fresh properties, the blocking ratio is then equal to 1.

Conversely, the blocking ratio is equal to 0 if the concrete is too stiff or segregated. Blocking ratio is useful for SCC applications involving complex shapes, and congested reinforcement.

The times for the concrete to flow along 200mm and 400 mm of the horizontal arm, T200 and T400 respectively, were used to evaluate the deformation rate previously but are not widely used now. Segregation can be visually checked. If the coarse aggregate is not evenly distributed along the trough or it is wedged between the reinforcing bars, this maybe an indicator of segregation. L-boxes of different sizes with different reinforcing bars and gaps were used. Investigations showed that the L-box was sensitive to blocking and that it was more difficult for concrete to pass three bars than the two bars (Sedran, Larrard, 1999).

The test depends on the operator, for example, in regard to the lifting speed of the gate (Nguyen et al., 2006). If the gate was lifted slowly and there was no segregation, the final shape of the concrete was determined by yield stress and there were correlations between blocking ratio to the ratio of yield stress to specific gravity; the difference between two results with and without steel bars were small which according to Nguyen et al., (2006) can be used to detect dynamic segregation.

Orimet test: The test is based on the principle of an orifice rheometer applied to fresh concrete (Bartos, 2000). The test involves recording of time that it takes for a concrete sample to flow out from a vertical casting pipe through an interchangeable orifice attached at its lower end. The shorter the Flow-Time, the higher is the filling ability of the fresh mix. The Orimet test also shows potential as a means of assessment of resistance to segregation on a site.

V-funnel test: Viscosity of the self-compacting concrete is obtained by using a V-funnel maximum aggregate diameter is 20 mm. The time for the amount of concrete to flow through the orifice is being measured. If the concrete starts moving through the orifice, it means that the stress is higher than the yield stress; therefore, this test measures a value that is related to the viscosity. If the concrete does not move, it shows that the yield stress is greater than the weight of the volume used. An equivalent test using smaller funnels (side of only 5 mm) is used for cement paste as an empirical test to determine the effect of chemical admixtures on the flow of cement pastes. Figure 2.4 has certain dimensions, in order for a given amount of concrete to pass through an orifice (Dietz, Ma, 2000). The amount of concrete needed is 12 litters.

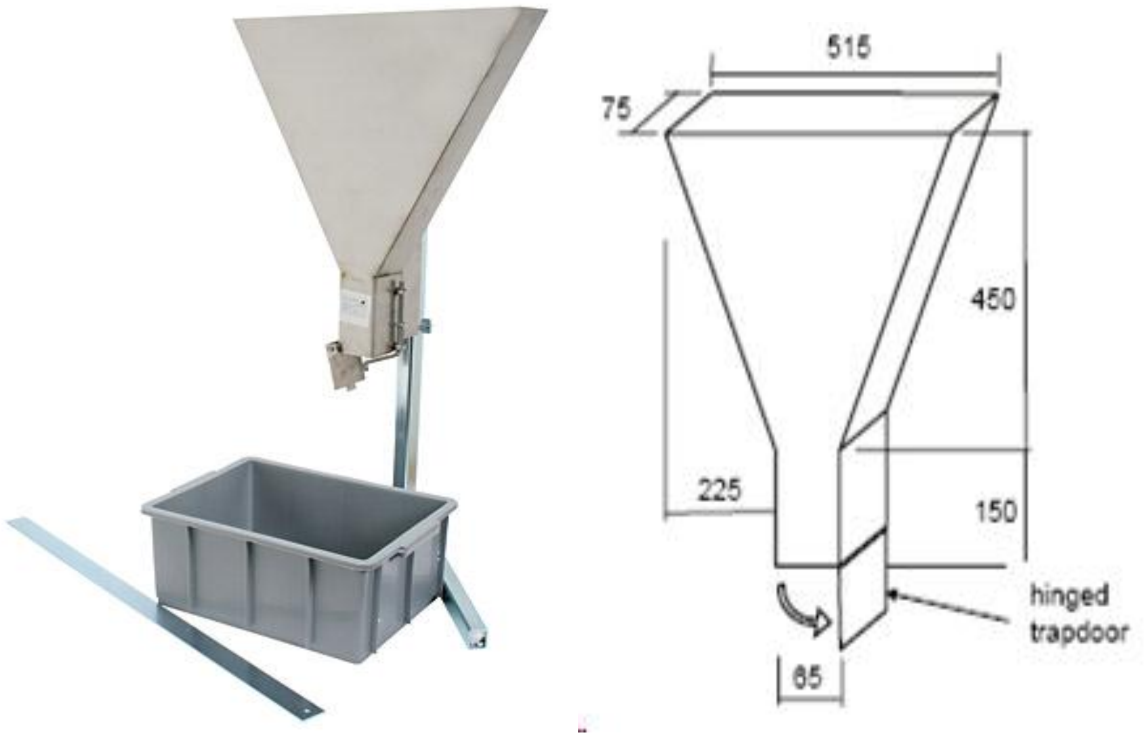

Fig 2.4: V-funnel (Dietz, Ma, 2000).

Slump Flow/J-Ring combination test: This test (Fig 2.5) involves the slump cone being placed inside a 300mm diameter steel ring attached to vertical reinforcing bars at appropriate spacing (the J-Ring itself) (Kosmatka et al., 2002). The number of bars has to be adjusted depending on the maximum size aggregate in the SCC mix. Like in the Slump Flow test, the diameter of the spread and the T-50 time are recorded for the evaluation of SCC viscosity. The Slump Flow/J-Ring combination test is an improvement upon the Slump Flow test on its own as it aims to assess also the passing ability of the fresh mix. In this respect, the SCC has to pass through the reinforcing bars without separation of paste and coarse aggregate.

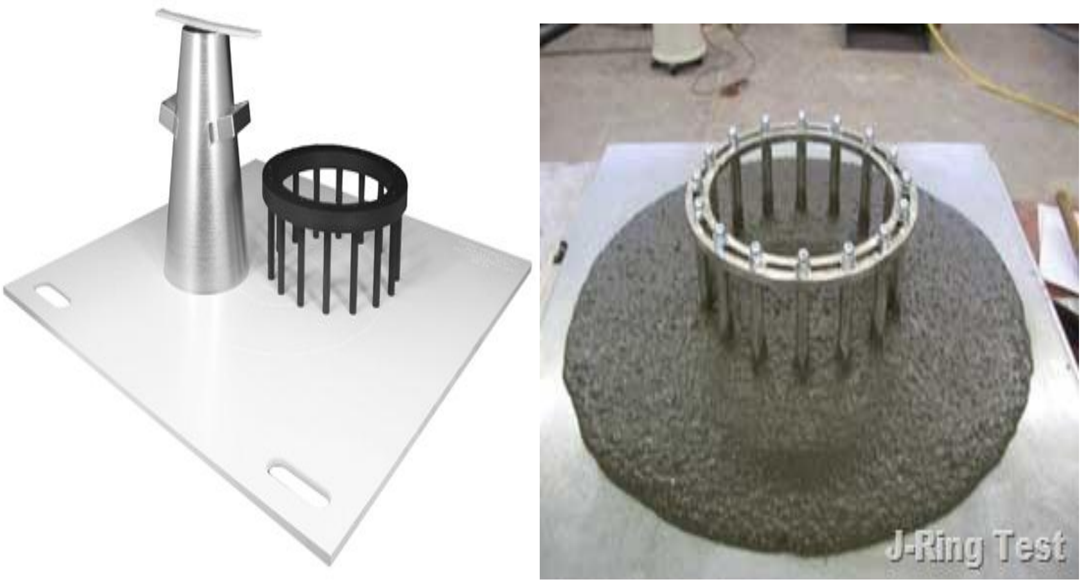

Fig 2.5: Slump Flow/J-Ring combination test (Kosmatka et al., 2002)**.**

Orimet/J-Ring combination test: This recently developed test involves the J-Ring being placed centrally below the orifice of the Orimet apparatus, allowing the discharged mix to fall into it and flow outwards. The Orimet time is recorded as in the conventional Orimet test, along with the diameter of the concrete spread and the height of the concrete within the J-Ring. The more dynamic flow of concrete in this test simulates better the behaviour of a SCC mix when placed in practice compared with the Slump-Flow variation. The Orimet/J-Ring combination test will be used in the future as a method of assessing filling ability, passing ability and resistance to segregation (Bartos, 2000).

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). 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.

Corinaldesi and Moriconi (2004) concluded fresh properties by using Portland–limestone blended cement, type CEM II/A-L 42.5 R according to the European Standards EN-197/1, its blaine fineness was 0.363 m^2/g and its specific gravity was 3050 kg/m^3. A commercial limestone powder, originating from marble, was used as a mineral admixture, its blaine fineness was 0.610 m^2/g. Crushed limestone aggregate (10-mm maximum size) and natural sand (6-mm maximum size) were used. A 40% aqueous solution of a melamine-based polymer was added to the mixture in order to guarantee very high workability. Straight steel fibres, with length and diameter of 11.0 and 0.4 mm, respectively, thus implying an aspect ratio (AR) equal to 28, were employed at a dosage of 0.6% by volume. This dosage was decided by carrying out preliminary tests, which confirmed that an increase in fibre content from 0.5% to 1%, results in lower concrete performance. Finally, a commercial product based on siloxanic resins was used to make the concrete surface hydrophobic. The mixture proportions of the self-compacting concrete are reported in Table 2.5, whereas its composition, expressed by volume percentage, is reported in Table 2.6. With respect to a common concrete (‘‘Ref-0.40’’ in Table 2.6), with the same water to cement ratio (0.40) and the same maximum size of aggregate particles (10 mm), a higher content of very fine material (cement and mineral additions) and a lower content of gravel (fraction with grain size higher than 5 mm) had to be used for Self-compacting concretes.

Table 2.5: Concrete Mix Proportions (Corinaldesi, Moriconi, 2004)

Concrete mixture proportions	
Water/Cement	0.40
Water/Fine material	0.34
Aggregate/Cement	3
Ingredients	
Water	200 lt
Cement	500 kg
Limestone powder	80 kg
Natural sand	1080 kg
Crushed aggregate	420 kg
Steel fibers	50 kg
Superplasticizer	9.4 lt

Table 2.6: Concrete composition by volume percentage (Corinaldesi, Moriconi, 2004)

	Ref-0.40	**SCC-0.40**
Water	19.1	20.6
Fine material [a]	15.6	19.1
Sand [b]	20.6	40.9
Gravel[c]	41.1	15.0
Steel fibers	-----	0.6
Superplasticizer	0.6	0.9
Air	3.0	2.9

[a] All materials passing through ASTM n ° 100 sieve of 150μm.

[b] All materials that can pass the sieve opening of 5 mm, keeping into account that almost 10% of crushed aggregate passes this sieve opening.

[c] All materials that cannot pass the sieve opening of 5 mm.

units in kg.

The water–cement ratio chosen was equal to 0.40, and the water–fine material ratio was 0.34 due to the addition of limestone powder at a dosage of 16% by mass of cement. In his work, VMAs were not employed; therefore, a very high content of materials passing through ASTM sieve of 150 μm was necessary, up to 19% by volume of concrete (see Table 2.6). Other conditions that should be respected in order to meet the self-compactability requirement concern the water–fine material ratio and the sand to mortar ratio; in his work, they were equal to 1.08 and 0.50, respectively and both expressed by volume percentage (see Table 2.6). In order to obtain a workability measured as high slump flow, a dosage of 1.6% by mass of cement of a melamine-based superplasticizer was necessary.

Slump flow test

As a first step, the properties of the fresh concrete was focused on the measurement of the slump flow, which is the mean diameter (Φ_{fin}) of the ‘‘cake’’ of concrete obtained after releasing of a standard slump cone. Then, the elapsed time to gain the mean diameter of 500 mm (t_{500}) and the elapsed time to gain the final configuration (t_{fin}) were also recorded.

L-box test

The ability of the concrete of compacting itself under its own weight was evaluated by means of the L-box with horizontal steel bars. Both the difference in the concrete level, between the beginning and the end of the box (ΔH_{fin}), and the elapsed time to establish the final configuration (t_{fin}) were detected.

Table 2.7: Fresh concrete workability results (Corinaldesi and Moriconi, 2004)

Fresh concrete workability: Results of slump flow and L-box tests		
Slump flow	Slump (mm)	290
	Φ_{fin} (mm)	650
	t_{500} (s)	2
	t_{fin} (s)	30
L-box	ΔH_{fin} (mm)	90
	t_{fin} (s)	30

Khatib (2008) took a total of 8 mixes that were employed to examine the properties of self-compacting concrete (SCC) with and without fly ash (FA). Details of mixes are given in Table 2.8. The constituents of mixes were Portland cement (PC), fly ash (FA), water, fine aggregate and coarse aggregate. The PC and FA complied with EN 197-1 and EN 450, respectively. The fine aggregate used conformed to class M of BS 882: 1992, and 10 mm nominal size crushed and washed was used as coarse aggregate. The only admixture (AD) used to produce self-compacting concrete was a liquid based on a modified synthetic carboxylated polymer. The AD conformed to Types A and F Admixtures of BS 5075 Parts 1 & 3 and EN 934-2:2000 with a relative density of 1.08.

Table 2.8: Details of mixes (Khatib, 2008)

Mix no.	**Proportions (% by mass of binder)**		**Content (Kg/m^3)**					
	PC	**FA**	**PC**	**FA**	**Water**	**Fag[a]**	**Cag[b]**	**AD[c] (%)**
M1	100	0	500	0	180	876	876	0.6
M2	100	0	500	0	180	876	876	0.7
M3	100	0	500	0	180	876	876	1.0
M4	80	20	400	20	180	845	876	0.7
M5	60	40	300	40	180	813	876	0.7
M6	40	60	200	60	180	782	876	0.7
M7	20	80	100	80	180	751	876	0.7

[a] fine aggregate, [b] coarse aggregate, [c] admixture, % by mass of binder

The control mixes M1–M3 had a proportion of 1 (PC): 1.75 (fine aggregate): 1.75 (coarse aggregate) without the inclusion of FA. Three different dosages of admixtures (AD) were used for these control mixes. The dosages of AD were 0.6%, 0.7% and 1.0% (by mass of PC) for mixes M1, M2 and M3, respectively. In mixes M4-M7, PC was partially replaced with 20%, 40%, 60% and 80% FA (% by mass of binder), respectively. The binder (b) consists of PC and FA. The dosage of AD for these mixes was 0.7% (by mass of binder). The water to binder (w/b) ratio for all mixes was maintained constant at 0.36 and no adjustment to the water content was made for mixes containing FA. All mixes exhibited high workability, in that the flow spread (i.e. diameter) for all mixes is in excess of 700 mm except for the control mix M1 where a spread of 635 mm is obtained where a relatively low dosage of AD is added (Table 2.8). These values are higher than those indicating elsewhere. Slump flow of 650 ± 50 mm is required for SCC, and all the mixes under investigation fall in this category. Visual examination of mixes containing FA suggest that there is further increase in workability, as demonstrated by the ease of flow in the moulds, compared with the control at the same dosage of admixtures (i.e. 0.7%). It is well established that the use of FA in concrete reduces the water demand for a given workability. Therefore, concrete containing FA will cause an increase in workability at constant water to binder ratio.

Nagataki, Fujiwara (1992) performed the slump flow test of SCC mix to find out whether the concrete mix is workable or not. They also performed the segregation test of SCC mix, by using locally available materials, the value ranging from 500-700 mm is considered as the slump required for a concrete to be self compacted.

Xie et.al (2000) reported the optimum mix parameters of high strength self –compacting concrete with ultra pulverized fly ash. All the materials used in this research were locally available. In this research cement was replaced by 30% of ultrapulverized fly ash of total cementitious material and sand was replaced by broken gravels. Superplasticizer content is 1.0-1.6 % of total cementitious material for water content of 175 l/m^3.When the superplasticizer content is higher than 1.9% compressive strength decreases because of bleeding. The results of this research indicates that higher the sand ratio, better the workability of fresh SCC, and smaller the compressive strength difference between SCC and normal concrete and the sand ratio cannot be less than 40%.

Felekoglu et al. (2005) has done research on effect of w/c ratio on the fresh and hardened properties of SCC. According to the author adjustment of w/c ratio and super plasticizer dosage is one of the key properties in proportioning of SCC mixtures. In this research, fine mixtures with different combinations of w/c ratio and superplasticizer dosage levels were investigated. The results of this research show that the optimum w/c ratio for producing SCC is in the range of 0.84-1.07 by volume. The ratio above and below this range may cause blocking or segregation of the mixture.

Pereira-de-oliveira et al. (2005) evaluated slump flow, L box, V funnel test to get the SCC workability. The characteristics and properties of mixtures are presented in the Table 2.9, being used, in accordance with the addition material used, abbreviations. SCCFA for self-compacting concrete with fly ash, SCCSF for Self-compacting concrete with silica fume, SCCHL for Self-compacting concrete with hydraulic lime and SCCFAHL for self-compacting concrete with a mixture of fly ash and hydraulic lime.

Table 2.9: Proportion in mass of the component materials of the tested mixtures (Pereira-de-oliveira et al. 2005)

Component	**NC**	**SCCFA**	**SCCSF**	**SCCHL**	**SCCFAHL**
Cement (Kg)	1.00	1.00	1.00	1.00	1.00
Fly ash (Kg)	xx	0.15	xx	xx	0.10
Silica lime (Kg)	xx	xx	0.10	xx	xx
Hydraulic lime (Kg)	xx	xx	xx	0.20	0.10
Sand (Kg) Mf* = 2,8	0.88	1.26	1.11	1.09	1.09
Sand (Kg) Mf* = 4,5	0.88	1.26	1.11	1.09	1.09
Aggregate 6-15 (Kg)	2.75	1.98	2.29	2.32	2.32
Water/Cement (Kg/Kg)	0.40	0.40	0.55	0.48	0.48
Superplasticizer Viscocrete 3000 (%)	1.50	2.5	2.2	2.4	2.4
Water/Powdered materials (Kg/Kg)	0.40	0.35	0.36	0.33	0.33

*Fineness module

Table 2.10 presents the results of tests carried out to verify the self-compacting of concrete. The results of slump-flow test carried out in SCC concrete characterize the mixtures as being Self-compacting. However, the mixture SCCSF and SCCFAHL presents relationships H_1/H_0 below 0.80. This value has been recommended as minimum value for this test that simulates the capacity of concrete transit inside the formwork and it depends on the steel bars density contained. In the funnel V test, the mixture SCCFAHL presented a lower fluidity, however the recommendation for this test result has been 10 ± 3 seconds.

Table 2.10: Results of Slump-flow, L box and V funnel tests (Pereira-de-oliveira et al., 2005)

Component		**NC**	**SCCFA**	**SCCSF**	**SCCHL**	**SCCFAHL**
Slump	(mm)	35	-	-	-	-
Slump	Time (sec)	-	4.81	1.34	2.53	3.29
Flow	Final average diameter (mm)	-	650	680	675	650
L-Box	T_{40} (sec) H_1/H_0 (cm)	-	5.46 0.86	3.93 0.60	2.81 0.86	4.00 0.50
V-Funnel	Time (sec)	-	10.00	13.00	12.29	15.00

Turk et al. (2007) for his study, three concrete types were selected, namely PC concrete, SCC-I and SCC-II. Fly ash and silica fume were used as cement component in SCCs. While the PC concrete contained combination of PC/FA (70/30%) and PC/SF (90/10%), respectively. Details of concrete mix compositions and properties of fresh concretes are given in Table 2.11 and Table 2.12 respectively.

Table 2.11: Mix proportions of concretes used (Turk et al., 2007)

Mix	**Cement (Kg/m^3)**	**FA (Kg/m^3)**	**SF (Kg/m^3)**	**W/B[a]**	**Sand (Kg/m^3)**	**Aggregates (Kg/m^3) 5-10**	**10-20**	**SP (l/m^3)**
PC	310	---	---	0.58	680	520	720	---
SCC-I	350	150	---	0.39	955	469	300	9.1
SCC-II	400	---	40	0.37	1090	470	335	8.4

[a] W/B is water to binder (PC+FA or PC+SF) ratio

Table 2.12: Properties of fresh concretes (Turk et al., 2007)

Mix	Slump (m)	T_{50cm} (s)	V-funnel		L-box		
			Flow time (s)	$T_{5\,min}$	H_2/H_1	T_{20} (s)	T_{40} (s)
PC	74	---	---	---	---	---	---
SCC-I	748[b]	3.6	8.00	11.0	0.94	1.4	2.8
SCC-II	685[b]	2.8	8.02	9.5	0.83	0.8	1.9

[b] Slump flow (mm)

Natural gravel with maximum particle size of 5-10 mm and 10-20 mm and natural sand (< 5 mm) were used for PC and SCCs. To achieve desired rheological behaviour for SCC, e.g. a slump flow value of 650-800 mm, a superplasticizer (Viscocrete 3075) was used in both SCC mixes, whilst the PC concrete did not contain superplasticizer. Mix designs for Self-compacting concretes were developed by means of trial mixes based on guidance given in EFNARC. For SCC, slump flow, t_{50} , L box and V funnel tests as described in EFNARC were carried out. The results obtained from these tests (Table 2.12) showed that SCC mixes had good filling and passing ability as well as segregation resistance.

Assie et al. (2007) has reported the Slump flow test, Segregation, Filling rate, Air content by using two types of cement i.e. :

- A CEM II/A-LL 32.5 R, containing 15.8% limestone filler, with a 28-day compressive strength of 45 MPa (Blaine fineness: 400 m^2/kg; density: 3030 kg/m^3). This lower cost cement is generally used in France for ordinary buildings subject to no severe exposure (class of concrete strength C20 or C25, according to EN 206-1;
- A CEM I 52.5 N, whose 28-day compressive strength was 63 MPa (Blaine fineness: 380 m^2/kg; density: 3130 kg/m^3). This cement is generally used for average and high-performance concrete (class of concrete strength C35–C60, according to EN 206-1.

The aggregates used were siliceous round aggregates of grade 0/4 mm for sand and 4/12 mm or 4/20 mm for the gravel. The limestone filler used in SCC mixes had the following characteristics: fineness 406 m^2/kg, density close to 2710 kg/m^3. A polycarboxylate modified superplasticizer was used as a water reducer in SCC and VC. Its density was 1.05, its chloride ion content was below 0.1% and it contained 20% of dry matter.

Mix proportions of SCC were chosen in accordance with the French recommendations as shown in (Table 2.13). The first results (Table 2.14) concern the workability of concrete characterized (according to AFGC recommendations by:

- Unconfined flowability, determined by the slump-flow test (the target values are generally in the range of 60 to 75 cm, with no visible segregation at the end of the test);
- Confined flowability, determined by the L-box test (the filling ratio must be greater than 80%);
- Stability, i.e. resistance to segregation and bleeding, determined by a specific French test called the screen stability test (the stability is satisfactory when the percentage of laitance by weight is lower than 15%, critical when the percentage of laitance is in the range of 15–30% and very poor when the percentage of laitance is higher than 30%).

Table 2.13: Mix proportions and Mix characteristics (Assie et al., 2007)

Mix proportions (Kg/m³)							
Composition (Kg/m³)		**Mix**					
		VC-20	**SCC-20**	**VC-40**	**SCC-40**	**VC-60**	**SCC-60**
Cement	CEM II/A-LL 32.5R	315	315	---	---	---	---
	CEM I 52.5 N	---	---	350	350	450	450
Limestone filler		---	150	---	140	---	70
Sand		981	900	962	888	751	884
Gravel	4/12 mm	---	---	857	791	1088	793
	4/20 mm	841	771	---	---	---	---
Superplasticizer		1.4	8.0	6.9	12.6	5.9	13.5
Water		189	205	175	191	164	189
Mix characteristics							
Properties		**Mix**					
		VC-20	**SCC-20**	**VC-40**	**SCC-40**	**VC-60**	**SCC-60**
Water/Cement ratio		0.60	0.65	0.50	0.55	0.36	0.42
Water/Binder ratio		0.60	0.65	0.50	0.50	0.36	0.40
G/S ratio (by mass)		0.86	0.86	0.89	0.89	1.45	0.90
Volume of paste (l/m³)		317	380	305	374	318	377

Table 2.14 shows that the SCC mixes complied with these AFGC recommendations. The VC mixes showed a somewhat high air content (due to air trapping as a secondary effect of the superplasticizer used when the slump was too low) and a slump characteristic of plastic to fluid concrete (class S_2 to S_3, according to the European standard EN 206-1. Moreover, these results show that SCC had a compressive strength similar to that of VC (for each strength class), a higher W/C ratio (but a similar W/B ratio).

Table 2.14: Concrete properties in fresh and hardened state (Assie et al., 2007)

Concrete properties in fresh and hardened state						
Properties	**Mix**					
	VC-20	**SCC-20**	**VC-40**	**SCC-40**	**VC-40**	**SCC-60**
Slump/Slump flow (cm)	12.5	67 (S.F.)	5 (S)	74 (S.F.)	14 (S)	70 (S.F.)
Segregation (GTM test, %)	---	0.6	---	7.8	---	2.2
Filling rate (L-box test)	---	0.80	---	0.92	---	0.87
Air content (%)	5.2	2.1	4.0	2.2	1.6	1.6
R_{C28} (MPa)	21.8	26.4	50.8	49.6	68.6	69.2

Siddique (2010) performed the results of various fresh properties tested by slump flow test, J-ring, L-box test, V-funnel test, U-box test for various mix compositions are given Table 2.15. The slump flow test judges the capability of concrete to deform under its own weight against the friction of the surface with no restraint present. A slump flow value ranging from 500 to 700 mm for a concrete to be self-compacting was suggested At slump flow >700 mm, the concrete might segregate, and at <500 mm, the concrete might have insufficient flow to pass through highly congested reinforcement. All the mixes in the present study conform to the above range since the slump flow of SCC mixes is in the range of 600–700 mm. The slump flow time for the concrete to reach diameter of 500 mm for all the mixes were less than 4.5 seconds. The J-ring diameter and difference in concrete height inside and outside J-ring were in the range of 540–625 mm and the difference in height was less than 40 mm. In addition to the slump flow test, V-funnel test was also performed to assess the flow ability and stability of the SCC. V-funnel flow time is the elapsed time in seconds between the opening of the bottom outlet depending upon the time after which opened (T10s and T5min) and the time when the light becomes visible from the bottom, when observed from the top. V-funnel time, which is less than 6 s, is recommended for concrete to qualify as a SCC. As per EFNARC, time ranging from 6 to 12 s is considered adequate for a SCC. The V-funnel flow times were in the range of 4–10 s. Test results of this investigation indicated that all SCC mixes meet the requirements of allowable flow time. Maximum size of coarse aggregate was kept as 16 mm in order to avoid blocking effect in the L-box. The gap between rebar in L-box test was 35 mm. The L-box ratio H2/H1 for the mixes was above 0.8 which is as per EFNARC standards. U-box difference in height of concrete in two compartments was in the range of 5–40 mm.

Table 2.15: Fresh properties of SCC mix. (Siddique, 2010)

Mix	**Slump Flow**		**J-Ring**		**V-funnel**		**L-Box**				**U-box**
	Dia. (mm)	**T50cm (s)**	**Dia (mm)**	**h2–h1 (mm)**	**T10s (s)**	**T5min (s)**	**T400mm (s)**	**T600mm (s)**	**TL (s)**	**(H2/ H1)**	**(H1–H2) (mm)**
SCC1	673	4.5	586	2	7.5	15.0	3.5	8	11.9	0.8	20
SCC2	690	3.0	580	6	4.5	5.1	1.4	2	3.5	0.9	10
SCC3	603	4.4	540	3	5.2	7.6	0.5	1	2.4	0.8	40
SCC4	673	3.0	626	3	6.1	9.5	1.2	2	4.0	0.9	5
SCC5	633	4.0	556	7	10.0	18.5	2.8	4	6.9	0.9	20

Liu (2010) studied that Due to its spherical shape, fly ash can disperse agglomeration of cement particles. When cement is replaced by fly ash, a lower dosage of super plasticiser and an increased quantity of water is therefore required to maintain the same filling ability passing ability is dependent on coarse aggregate content and viscosity. The step height of the J-ring test, which gives an indication of the passing ability increased from 11 mm (F0) to 22 mm (F100) for SCC with cement only and with fly ash only respectively. The difference of 11 mm is higher than the typical within-test variation of 8 mm reported by Bartos. If the difference does not come from variation of the test method itself, it should result from the difference between two mixes. F100 has a higher W/P ratio and a lower super plasticiser dosage than F0. The combined influences of an increase in fly ash content and W/P ratio and a decrease in super plasticiser dosage lead to the increased viscosity and hence the increase in step height as the coarse aggregate content is constant. There is an improvement in segregation resistance for the SCC mixes incorporating 80% and 100% fly ash. The segregation index of these mixes is only 5–7% which is low. This is in line with the results from Bouzoubaa and Lachemi that for SCCs with fly ash, segregation index decreased with an increase in fly ash which accompanied an increase in the super plasticiser content and a decrease in the W/P ratio. The other study showed that segregation resistance was related to the passing ability and viscosity of SCC. As stated above, these mixes have higher viscosity than those incorporating up to 60% fly ash. This can result in lower segregation. To assess the consistence retention, the slump flow and the V-funnel time measured at 65 ± 5 min after addition of the water that after about an hour, slump flow decreases and v-funnel time increases, which means that the filling ability decreases with time. They should behave the same in all fresh concrete properties. However, the results of step height in the J-ring test, the sieve segregation, and the slump flow and the v-funnel time 65 min after mixing clearly showed that target SCCs did not have the same passing ability, segregation resistance and consistence retention.

Domone (2006) conducted slump flow test, which measures the flow capacity, has been universally used, and hence values of slump flow spread. Nearly 50% of the applications used values in the range 650–700 mm, with nearly 90% in the range 600–750 mm . Flow rate values, expressed either as T500, V- or O-funnel or Orimet times, were reported in about half of the case studies. They varied considerably; T500 times ranged from 1.8 to more than 12 s and V-funnel or O-funnel times from 3 to 15 s; there is thus a wide range in this property. There was no pattern of higher slump flows being associated with lower flow rate values, indicating the independence of these properties, and the ability to design mixtures with a combination thought suiTable for a given application.. L box blocking ratio values were all in excess of 0.8; U-box values were in excess of 300 mm, with the reinforcement spacing varied in some cases to suit the application.

2.3 HARDENED CONCRETE PROPERTIES

2.3.1 Compressive Strength

Siddique (2010) investigated the compressive strength tests results of SCC mixes are given in Table 2.16 and shown in Fig 2.6 With the increase in fly ash content from 15–35%, SCC mixes developed compressive strengths between 29.5 and 22.8 MPa at 7 day; between 35.2 and 29.6 at 28 day; between 58.9 and 40.8 at 90 day; and between 61.2 and 43.7 MPa at 365 day. The compressive increased with a decrease in the percentage of the fly ash and the water-to-cementitious materials ratio. An increase of about 18% strength at 28 days and 40% at 365 days was observed with the decrease of fly ash content from 35% (SCC1) to 15% (SCC5). The strength values at 7 days of SCC5 (35% fly ash) are comparable with the results for the replacements with fly ash at 40% of total powder content. But strength at 28 days was found to be lower since no VMA and AEA was added to the SCC mixes. It was observed that the strength gain at 90 days and 365 days was within the limits corresponding to the amount of cement content used in the SCC mixes. For the same mix, the strength values corresponded to those at 28 days age of curing. SCC4 (30% fly ash) attained strength of 23.98 MPa, 30.66 MPa, 41.96 MPa and 44.84 MPa at 7, 28, 90, and 365 days, respectively. Similarly, SCC 3 (25% fly ash) attained strength corresponding to 25.52 MPa, 31.47 MPa, 43.77 MPa and 46.47 MPa, at 7, 28, 90, and 365 days, respectively. For the SCC 2 (20% fly ash) mix, at 19% cement replacement by fly ash in total powder content. The strength of SCC 2 (20% fly ash) in the study at 28 days was 33.15 MPa whereas at 90 days was 52.86 MPa which was much higher content in the mix.

Table.2.16: Compressive and splitting tensile strength of SCC mixes (Siddique, 2010)

Mix	**Compressive strength (MPa)**				**Splitting tensile strength (MPa)**		
	7days	28days	90days	365days	28days	90days	365days
SCC1	29.55	35.19	58.99	61.24	2.40	2.68	2.96
SCC2	27.99	33.15	52.86	54.60	2.12	2.33	2.61
SCC3	25.52	31.47	43.76	46.67	1.83	2.12	2.33
SCC4	23.98	30.66	41.96	44.87	1.76	1.97	2.26
SCC5	22.78	29.62	40.88	43.73	1.55	1.76	2.12

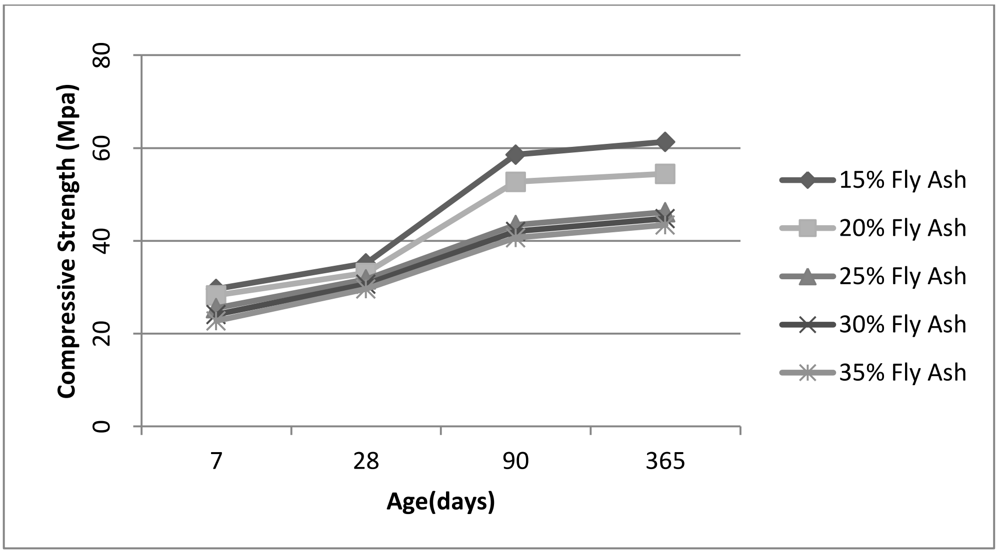

Fig 2.6: Compressive strength of SCC mixes at various ages (Siddique, 2010)

Khatib (2008) investigated the effect of different dosages of AD on concrete strength for the control mixes (M1–M3) is shown in Fig 2.7. Using either a relatively low or high dosage of AD reduces the strength, whereas using an optimum dose of AD (e.g. 0.7%) causes an increase in strength. As suggested earlier, low dosage might lead to the creation of pore if concrete is to be compacted under its own self-weight only, whereas high dosage might lead to segregation. This can justify the relatively high strength obtained when a medium dose of AD (0.7%) is added to the concrete. Fig 2.8 shows the influence of FA incorporation on concrete strength at a constant addition of AD (0.7%). Concrete containing 40% FA shows higher 56 days strength than the other FA mixes including the 20% FA mix, whereas high strength of approximately 70 N/mm^2 at 56 days is obtained. Generally and at the same water to binder ratio, there is strength reduction for concretes containing FA compared with that of the control. However, and even at high FA content (60%), a long-term high strength of about 40 N/mm^2 is achieved at the same water to binder ratio. Higher strength would be expected in the FA mixes if the w/b ratio was lowered to achieve similar workability to that of the control. The trend is similar to results obtained elsewhere on SCC containing FA. Correlation between strength and water absorption for all mixes (M1–M7) is shown in Fig 2.9. As can be expected, an increase in strength is associated with a decrease in water absorption. There is sharp decrease in strength as the absorption increases from 1% to 2%. For absorption beyond 2%, there is a much slower reduction in strength with the increase in absorption.

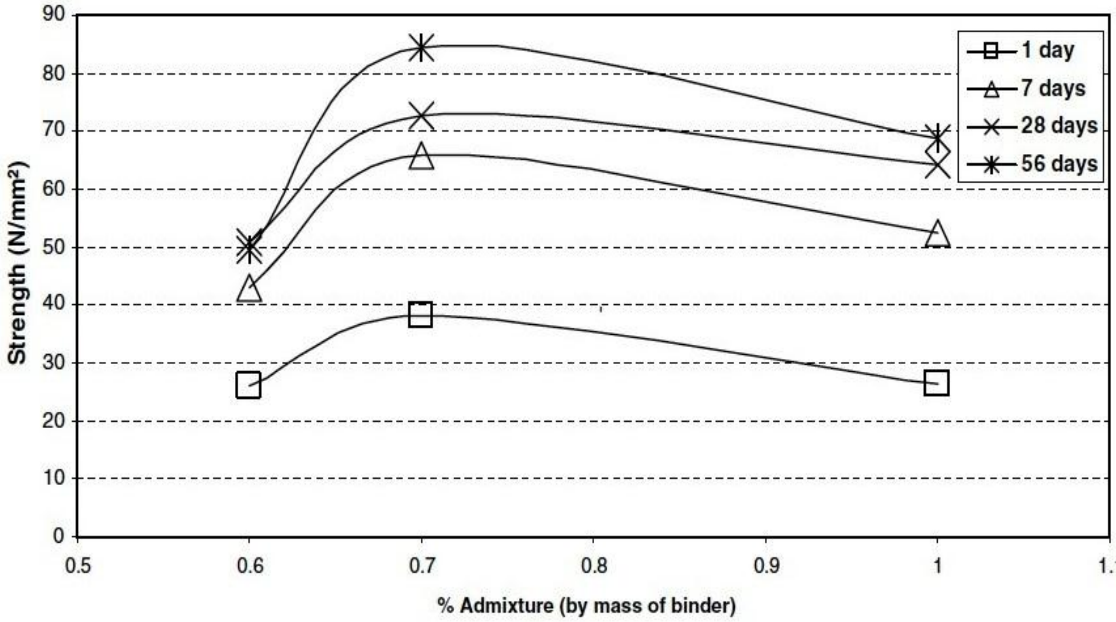

Fig 2.7: Influence of admixture dosage on strength (Khatib, 2008)

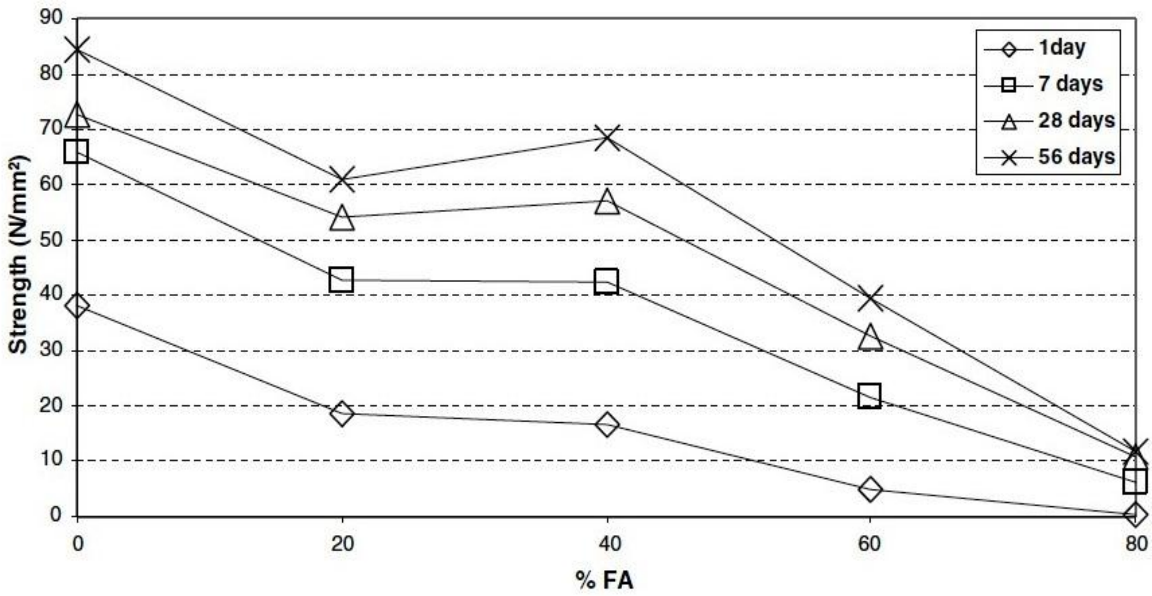

Fig 2.8: Influence of FA content on strength (AD = 0.7%) (Khatib, 2008)

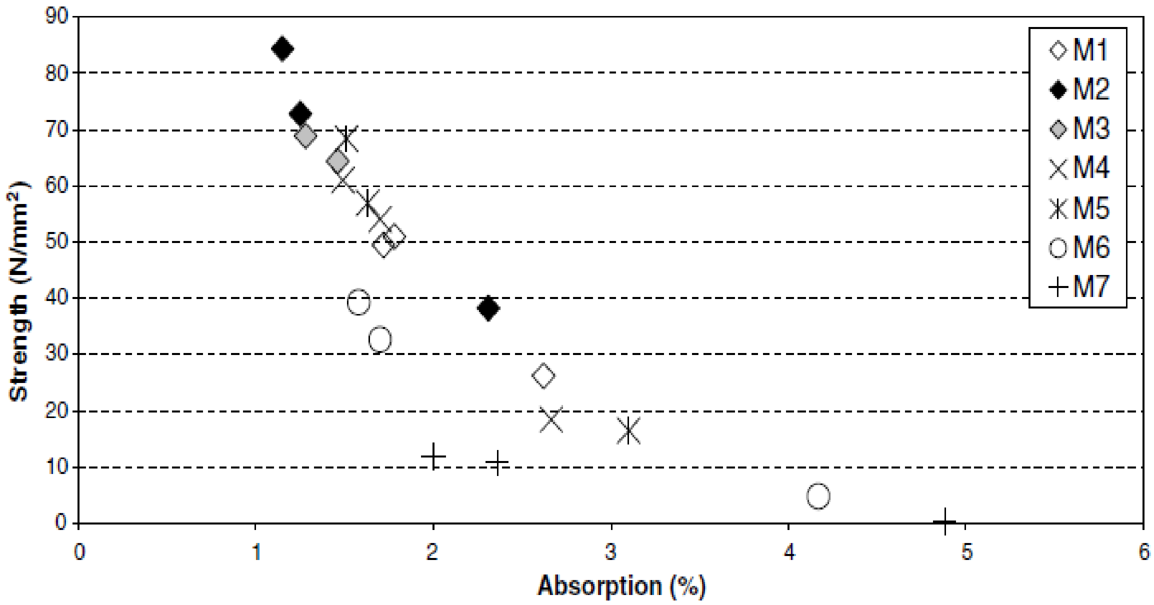

Fig 2.9: Relationship between strength and absorption. (Khatib, 2008)

Naik and Singh (1997) conducted tests on concretes containing between 15% and 25% by mass Class F and Class C fly ashes to evaluate compressive strength. 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. The air-cured concretes containing Class F fly ash did not develop strengths equivalent to air-cured normal concretes and air-cured concretes containing Class C fly ash developed relatively greater compressive strengths than air-cured concretes containing Class F fly ash. For concretes containing either class of fly ash, compressive strengths at 7 days increased with an increase in curing temperature.

Kraus et al. (2009) used Type I portland cement (ASTM C 150) his research. The fine aggregate used was natural sand with fineness modulus of 2.74, bulk density of 1710 kg/ m^3, specific gravity of 2.73, and SSD absorption of 1.3%. Pea gravel was used as coarse aggregate, which had a nominal maximum size of 9.5 mm, bulk density of 1700 kg/m^3, specific gravity of 2.68, and SSD absorption of 2.3%. ASTM Class C fly ash received from

We Energies' power plant in Oak Creek, Wisconsin, USA, was used. The amount of the fly ash retained when wet-sieved on a 45-µm sieve was 13%. The strength activity index of fly ash (or, compressive strength of mortar made by replacing 20% of cement with fly ash) was 104% and 113% of the strength of control mortar at 7 days and 28 days, respectively. A polycarboxylate HRWRA and a VMA were also used. The foundry baghouse silica-dust used in this research was ''sand system baghouse dust" received from an iron foundry in Wisconsin, USA. As-received moisture content of the foundry baghouse dust was approximately 2%. Table 2.17 presents the results of chemical analysis of portland cement, fly ash, and foundry silica-dust.

Table 2.17: Chemical analysis of materials (Kraus et al., 2009)

Material	**Type I Portland cement**	**Class C fly ash**	**Iron-foundry silica-dust**
SiO_2	20.0	35.8	51.6
Al_2O_3	4.8	20.6	12.1
Fe_2O_3	2.1	5.8	6.4
$SiO_2 + Al_2O_3 + Fe_2O_3$	Not applicable	62.2	70.1
MnO	0.1	0.0	0.1
MgO	2.2	5.6	2.1
CaO	66.0	24.7	2.5
Na_2O	0.2	2.2	1.3
K_2O	0.5	0.5	0.7
TiO_2	0.2	1.5	0.5
P_2O_5	0.0	1.0	0.1
SO_3	2.5	1.2	0.8
Loss on ignition	1.4	1.2	22.0

The foundry baghouse dust was coarser than the Class C fly ash. The mean particle size (D50) of the foundry dust was about 75 µm. The amount of fines smaller than 125 µm in diameter is considered as powder and is very important for the rheology of SCC. A certain minimum amount of fines arising from cementitious materials, fillers, and sand is needed to avoid segregation. Approximately 74% of the foundry silica-dust was finer than 125 µm. Quartz, traces of calcite, anorthite, and muscovite were found in the foundry silica-dust. Infrared spectrometry showed C–O bond at 1453 cm^{-1}, and the presence of organics was high (22%), as measured by loss on ignition of the foundry dust. The strength activity index of the foundry silica-dust was not evaluated.

The reference SCC mixture was made containing 40% Class C fly ash by mass of total cementitious materials. Three more SCC mixtures were made using foundry bag house silica-dust as a fly ash replacement material. A replacement ratio of 1:2 (fly ash to foundry dust) by mass was used for the replacement of 10%, 20%, and 30% of Class C fly ash. The additional foundry silica-dust was treated as very fine sand. Table 2.18 presents the mixture proportions and other details of the SCC mixtures. The amount of sand in the reference mixture was higher than the SCC mixtures made with foundry silica-dust.

Table 2.18: Mixture proportions (Kraus et al., 2009)

Mixture designation	**Refrence**	**Fd-1**	**Fd-2**	**Fd-3**
% Replacement of fly ash with foundry silica dust	0	10	20	30
Cement (Kg/m^3)	265	262	261	252
Class C fly ash (Kg/m^3)	178	157	138	115
Sand (Kg/m^3)	923	801	796	734
Foundry silica dust (Kg/m^3)	0	37	73	106
Pea gravel, 9.5-mm max (Kg/m^3)	845	829	824	797
Water (Kg/m^3)	142	138	138	132
HRWRA (L/m^3)	4.8	4.1	5.6	9.9
VMA (L/m^3)	3.0	2.6	2.5	2.0
Water /(cement + fly ash) w/cm	0.33	0.34	0.36	0.38

All the ingredients except the chemical admixtures of the SCC mixtures were mixed in a dry state for about 30 s in a tilting drum type concrete mixer. Then three quarters of total water required was added in the mixer and the mixture was further mixed for three minutes followed by three minute rest. The chemical admixtures (i.e., HRWRA and VMA) were mixed thoroughly in the remaining water and then the water was added to the mixture and the mixing was further continued for about three to four minutes before evaluating the self-consolidating characteristics of the concrete. The self-compacting characteristics of the concrete mixtures were evaluated by using slump-flow and U-box tests as per the procedure mentioned in EFNARC and while the air content and density were determine as per the procedure of ASTM C 138. The tests results are presented in Table 2.18 Cylindrical specimens (100 x 200 mm) were prepared for the evaluation of the compressive strength of concrete. The specimens were demolded after 24 h of casting and kept in a curing room with RH not less than 95% and temperature of 20 ± 2 ºC till testing.

The compressive strength and material cost of SCC mixtures are shown in Table 2.19. Compared with reference mixture, some reduction in the 3-day strength and considerable reductions in the 7-day and 28-day strengths were observed when 10–30% of fly ash was replaced with foundry silica-dust. This was attributed to the higher air content and lower density and increased water to cementitious material ratio, of the SCC mixtures containing foundry silica-dust and the reduction in fly ash content. Further, perhaps organic contaminants in the foundry dust might have also contributed to strength reductions due to interference with cement hydration reactions.

Table 2.19: compressive strength of SCC mixtures (Kraus et al., 2009)

		Reference	**Fd-1**	**Fd-2**	**Fd-3**
1.	3-day comp. strength (MPa)	28.6	23.2	25.3	19.1
2.	7-day comp. strength (MPa)	43.5	32.0	36.4	26.7
3.	28-day comp. strength (MPa)	62.4	42.3	47.1	34.1

Some reduction in 3-day compressive strength and a considerable reduction in 28-day compressive strength were observed which might be due to increased air content, reductions in concrete density and fly ash content, as well as the interference of organic impurity of foundry dust with cement hydration reactions. Thirty percent replacement of fly ash by foundry silica-dust limits its uses options.

Felekoglu (2008) prepared all the mixtures by using an Ordinary Portland Cement (CEM I 42.5) in conformity with TS EN 197-1 standard. In order to enhance the paste content, a C-type fly ash which conform the TS EN 450 standard requirements was employed. Its specific gravity and Blaine fineness were 2.2 and 290 m^2/kg, respectively. A crushed limestone coarse aggregate with a specific gravity of 2.70 and water absorption of 0.5% was used in all mixtures. An F-type high range water reducing admixture in conformity with ASTM C 494 standard was also employed. The solid content and the specific gravity of this admixture was 39.7% and 1.10%, respectively. Four different sands were used. These are named as washed natural (WN) sand, washed crushed limestone (WCL) sand, crushed limestone sand with silt powder (CLS) and crushed limestone sand with clay powder (CLC). The physical properties of sands were determined by using TS 706 EN 12620 concrete aggregates standard.

Eight self-compacting concrete mixtures were prepared at two strength grades. The strength grades were named as low-I and high-II. The water/cement ratios (W/C) of low and high strength grade mixtures were 0.66 and 0.55, respectively. The mixture proportions are given in Table 2.20. The self-compactability of mixtures was obtained by increasing the admixture dosage. Admixture requirements of all mixtures to reach the slump-flow value of 720±20 mm were determined. The slump-flow, T50 time and L-box passing ability tests were performed by using EFNARC standards. Additionally the visual stability indices were determined and air content of fresh concrete was measured by using ASTM C231 standard.

After the completion of initial fresh concrete and mortar tests, self compactable mixtures were poured into cubic moulds of 150 mm without any vibration and compaction. Specimens were demoulded 24 h after casting. After demoulding, specimens were cured in lime water until the day of testing. The average compressive strength test results for different ages (2, 7 and 28 days) were determined by using three specimens for each age.

Table 2.20: Mix proportions of SCCs (Felekoglu, 2008)

	WN-I	**WN-II**	**WCL-I**	**WCL-II**	**CLS-I**	**CLS-II**	**CLC-I**	**CLC-II**
Mixture proportions (Kg/m^3)								
Cement	326	337	325	336	326	336	324	333
Fly ash	167	173	167	173	167	173	167	171
Water	214	186	214	186	214	186	213	184
Coarse aggregate	660	683	660	682	660	682	657	676
Sand	884	914	884	912	884	912	879	904
Admixture	5.0	7.4	5.3	8.0	7.4	9.9	11.7	15.2

The compressive strength developments of SCC mixtures are presented in Fig 2.10. Significant compressive strength reductions were observed from mixtures prepared with CLC sand. When compared with WN sand, the 28 days strength loss of SCCs incorporating CLC was as high as 30–40%. On the other hand, the strength differences between WN, WCL and CLS sand incorporated concretes were not significant at both strength classes (I and II). These concretes can be accepted as the same strength grade mixtures.

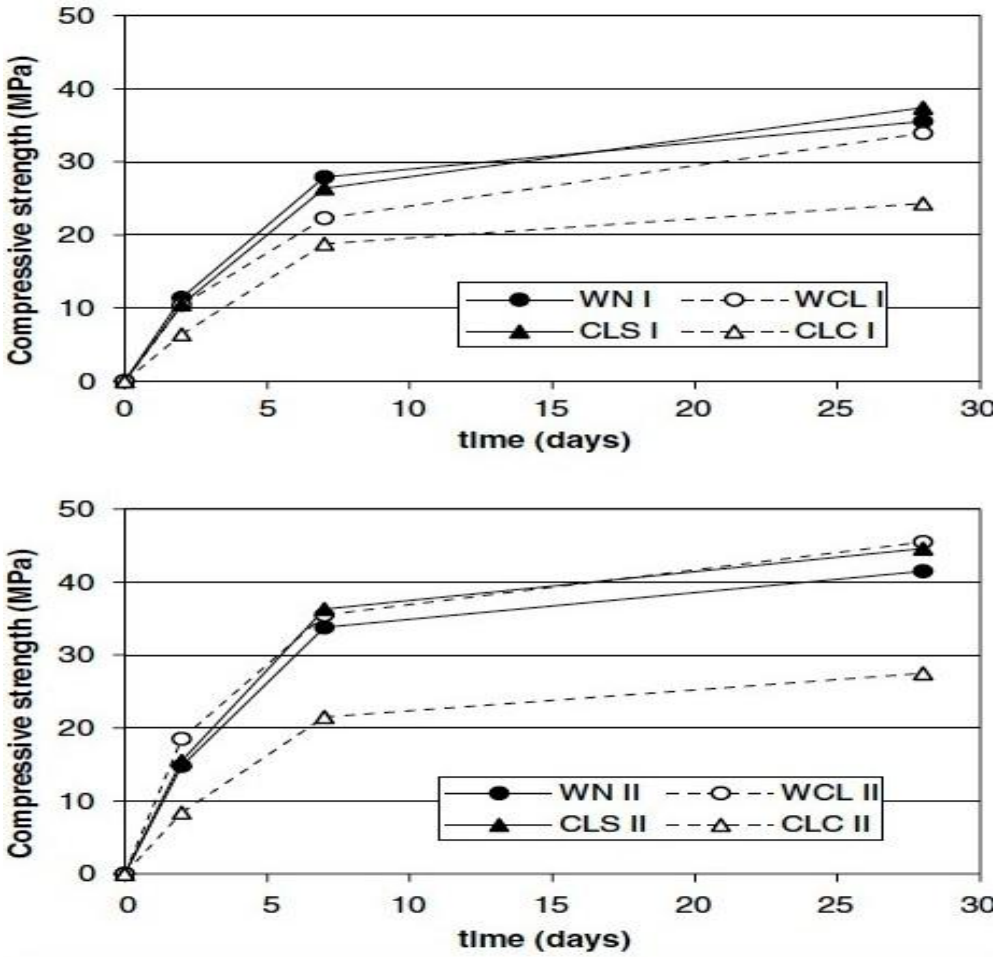

Fig 2.10: The Compressive strength evaluation of SCC mixture prepared with Different sands (Felekoglu, 2008)

Turk et al. (2007) used standard 150 mm cube and cylindrical (with diameter of 150 mm and a height of 300 mm) specimens. In the following day of casting, the specimens were demoulded and located in three different curing conditions, namely standard 20ºC water, sealed and air cured for the periods of 3,7, 14 and 28 days. The results obtained from compressive strength tests on PC, SCC-I and SCC-II for all concrete ages and curing conditions are given in Fig 2.11 a, b and c respectively. It can be seen in these Figs that the compressive strength results of SCC-I and SCC-II specimens (with w/b ~ 0.38) were higher than those of corresponding PC specimens (with w/b ~ 0.58) for all curing methods, it is also indicated that the highest compressive strength values were obtained from water cured specimens followed by the sealed and air cured specimens regardless of the concrete types. This shows the role of curing methods on the early ages compressive strength of concretes, i.e., the higher the compressive strength was achieved. When the SCCs are compared, it can be seen that the SCC-II containing 10 % of SF as a cement component provided higher compressive strength than those of SCC-I containing 30% of FA, regardless of curing conditions indicating the role of SF in strength development.

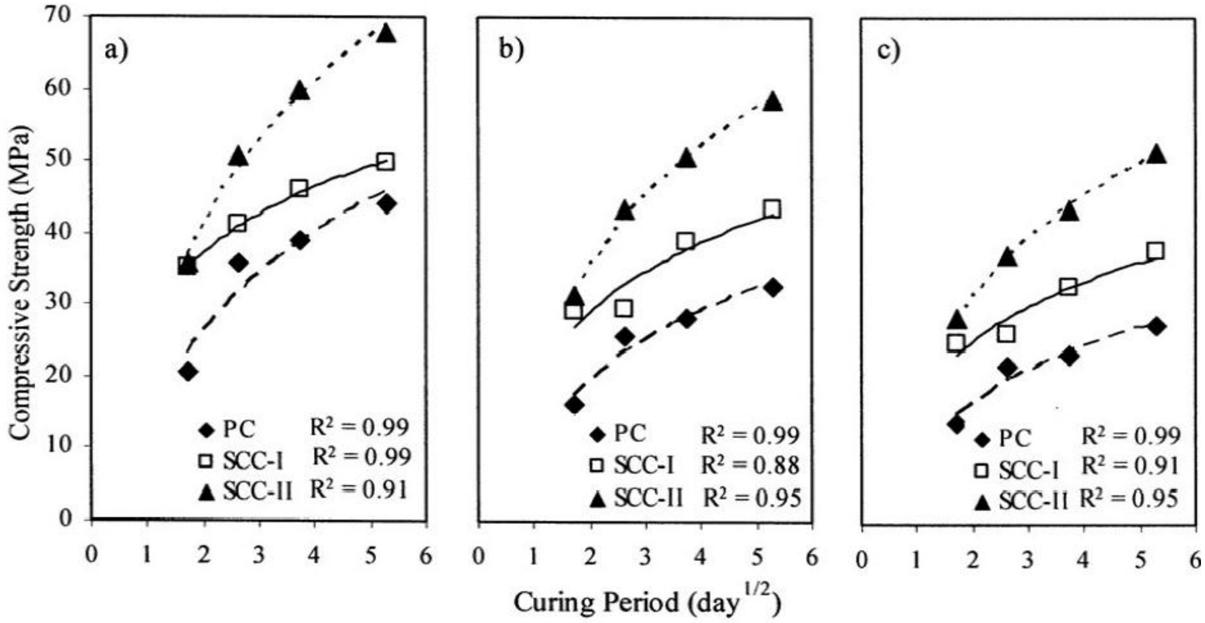

Fig 2.11: Compressive strength of PC and SCCs for all curing methods (a) water, (b) sealed and (c) air (Turk et al. 2007).

2.3.2 Water Absorption

Dinakar et al. (2008) performed water absorption studies by using Ordinary Portland cement (similar to ASTM Type I) conforming to the requirements of IS: 12269 (53 grade) was used. Fly ash meeting the requirements of ASTM C 618 (Class F) was used. Crushed granite with maximum grain size of 12 mm for SCC and 20 mm for normally vibrated concrete (NC) and good quality well graded river sand were used as coarse and fine aggregates, respectively. The coarse and fine aggregates had specific gravities of 2.68 and 2.65, respectively. The high range water reducer (HRWR) used in this study was a commercially available sulphonated naphthalene formaldehyde (SNF) condensate. Eight different Self-compacting fly ash concretes were designed at varying fly ash dosages. In addition five different normal vibrated concretes were also designed. The details of concretes of different strengths with the different percentages of replacement are given in Table 2.21. To develop a comprehensive understanding, a wide spectrum of concrete strengths were taken (from 20 to 100 MPa) with fly ash replacements also ranging from 0 to 85%, depending upon the maximum replacements possible at any strength. The advantage of this methodology is that at higher replacement percentages the Self-compacting concretes are more economical. However, this would require specific adjustments to all the other ingredients like sand, coarse aggregate, superplasticizer and water, to arrive at an optimal mix proportion.

Table 2.21: Mix proportions (Dinakar et al., 2008)

No	Concrete grade (MPa)	Concrete name	TCM (p) (Kg/m^3)	Fly ash (%)	Cement (Kg/m^3)	Total aggregate (Kg/m^3)	W/P ratio	HRWR liquid weight (%)
1.	20	NC20	234	0	234	1874	0.79	0
2.		SCC558	550	85	83	1418	0.41	2
3.	30	NC30	319	0	319	1681	0.58	0
4.		SCC557	550	70	165	1491	0.34	2
5.		SCC757	750	70	225	1107	0.33	2
6.	60	NC60	500	0	500	1462	0.37	0
7.		SCC555	275	50	275	1571	0.34	2.5
8.		SCC655	325	50	325	1388	0.34	2
9.	90	NC90	552	0	552	1465	0.29	1
10.		SCC553	385	30	385	1663	0.31	2.5
11.		SCC530	350	30	350	1608	0.36	1.75
12.	100	NC100	659	0	659	1334	0.22	1
13.		SCC551	495	10	495	1718	0.29	3

Percentage of water absorption and percentage of permeable voids were determined as per the procedure given in ASTM 642–82. The absorption and permeable voids were determined on two 100 mm cubes. Saturated surface dry cubes were kept in a hot air oven at 105ºC till a constant weight was attained. The ratio of the difference between the mass of saturated surface dry specimen and the mass of the oven dried specimen at 105ºC to the volume of the specimen (1000 ml) gives the permeable voids in percentage as given below:

$$\text{Permeable voids} = [(A-B)/V] \times 100$$

Where, A = weight of surface dried saturated sample after 90 days immersion period.

B = weight of oven dried sample in air.

V = Volume of sample (considered as 1000 ml).

The oven dried cubes after attaining constant weight, were then immersed in water and the weight gain was measured at regular intervals until a constant weight was reached. The absorption at 30 min (initial surface absorption) and final absorption (at a point when the difference between two consecutive weights at 12 h interval was almost negligible) was determined. The final absorption in all cases was determined at 96 h. The absorption characteristics indirectly represent the volume of pores and their connectivity.

The results of water absorption in 30 min (initial surface absorption) as well as the absorption after 96 h (final absorption) are as follows.

Table 2.22: Water absorption initial and final reading data (Dinakar et al., 2008)

No.	**Name**	**30 Min.Abs. (%)**	**Final Abs. (96 h) (%)**
1.	NC20	0.86	4.92
2.	SCC558	2.51	8.84
3.	NC30	1.23	4.93
4.	SCC557	0.83	4.91
5.	SCC757	1.49	4.12
6.	NC60	0.86	2.98
7.	SCC555	1.30	4.61
8.	SCC655	1.19	4.06
9.	NC90	0.55	1.68
10.	SCC553	1.21	4.69
11.	SCC530	0.78	4.33
12.	NC120	0.69	2.15

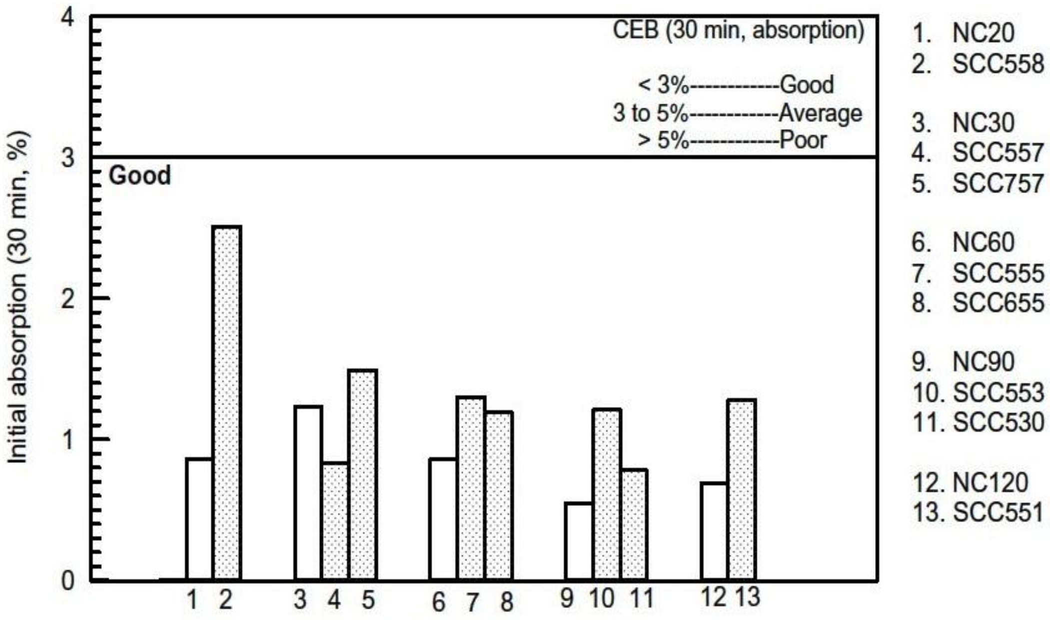

Fig 2.12: initial absorption values of concretes investigated (Dinakar et al., 2008)

From these results it can be seen that the low strength concretes were showing higher absorption than high strength concretes. Fig 2.12 presents the values of 30 min (initial) absorption of all the concretes. The initial absorption values of all the Self-compacting fly ash concretes were slightly higher than the normal vibrated concretes and the absorption increased with an increase in percentage of fly ash replacement. Fig 2.12 also presents the recommendations given by Concrete Society (CEB, 1989) for absorption 30 min. This shows that all the Self-compacting fly ash concretes as well as normal vibrated concretes had lower absorption than the limit specified for ‘‘good” concretes. The final absorption at the end of 96 h also followed a similar trend. The 20 MPa SCC (SCC558) showed the highest absorption (8.84%) than any other concrete. This may be due to the very high amount of fly ash (85%) in the system. Except 20 MPa SCC, the final absorption values of all the other grades of SCC (30–100 MPa) were similar, but these were always higher than the normal vibrated concretes at any particular strength. Except 20 MPa grade, the final absorption values of SCCs lie in the range 4.06-4.91%, whereas the corresponding normal vibrated concretes showed absorption values around 1.68-4.93%. Water absorption is mainly influenced by the paste phase; primarily, it is dependent on the extent of interconnected capillary porosity in the paste. Concrete mixes with higher paste contents are bound to have higher absorption values than concretes with lower paste content (at consistent w/c). The lower water absorption thus observed for normal vibrated concretes is attributed to the relatively lower paste volume i.e., smaller capillary pore volume. It is noted that Self-compacting concretes with fly ash have higher water absorption. The increase in paste volume due to the lower specific gravity of fly ash contributes to an increased capillary pore volume and increased water absorption.

Felekoglu (2008) also conducted water absorption studies by using wet sieved mortar portions of SCCs. Half of the separated mortars were poured into cubic moulds of 50 mm. Specimens were demoulded 24 h after casting. After demoulding, specimens were cured in lime water for 28 days. These specimens were oven dried and fully immersed into water for 24 h. Weight gains were measured.

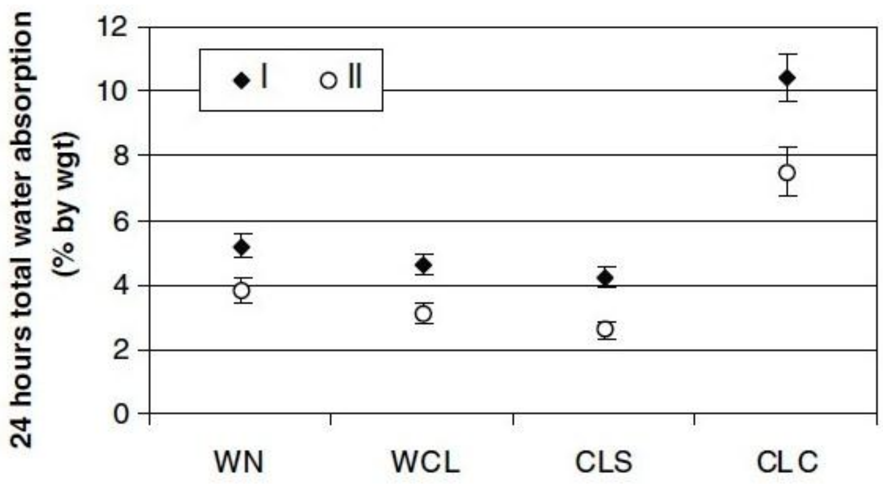

Fig 2.13: Twenty-four hour water absorptions of SCCs (Felekoglu 2008)

Water absorption test results were presented in Fig 2.13. Slight reductions in water absorption values compared to SCC mortars with washed sands were obtained from SCC mortars of CLS sand. This result is in consistency with the literature advocating the pore filling effect of fine fillers. On the other hand, significantly higher water absorption was observed when CLC sand was employed (Fig 2.13). The possible mechanism of increased water absorption of mortars of CLC sand will be discussed in relation with the microstructural characteristics of this fine portion in the subsequent section.

Assie et al., (2007) mixed concrete using a 125-l vertical-axis planetary mixer. The mix sequence was as follows. First, the dry aggregates were humidified for 10 min, and then cement was introduced and mixed with the aggregates for 30 s. The water and part of the additives were then introduced and mixed for a further 90 s. Finally, the remaining additives were added and mixed with the batch for 2 min. The samples of VC were set up using vibration (vibrating switches or Tables) and those of SCC were set up only by gravity, with no vibration. Afterwards, specimens were stored for 24 h in a room maintained at 20ºC without humidity exchange (the low bleeding of SCC makes it more vulnerable to the effects of plastic shrinkage). They were then demoulded and stored in a wet room at 20 ± 1ºC and 100% RH.

Water porosity was calculated from three masses (weighed hydrostatically or in air): apparent mass of saturated concrete samples (5 cylinders Φ15 x H5 cm) after immersion (liquid saturation under vacuum) (M_{water}), mass in the air while they were still soaked (M_{air}) and mass of dry samples (drying at 80 ± 5ºC until they reached a constant mass) (M_{dry}).Water absorption (ε) is given by the following equation:

$$\varepsilon = \frac{M_{\text{air}} - M_{\text{dry}}}{V} = \frac{M_{\text{air}} - M_{\text{dry}}}{M_{\text{air}} - M_{\text{water}}} \times \rho_{\text{water},\theta} \times 100$$

where, ρ_{water}, θ denotes the density of water at testing temperature (θK).

Khatib (2008) observed that the influence of varying AD content on absorption is shown in Fig 2.14 (mixes M1–M3). There is a decrease in absorption with the increase in curing period and this decrease is substantial between 1 day and 28 days.

As can be expected the prolonged curing period (56 days) led to lower absorption compared with that obtained at 28 days of curing. Using an optimum dosage of AD (e.g. 0.7%) causes a decrease in absorption compared with a relatively low (0.6%) or high (1.0%) dosage of AD. The use of low dosage of AD may cause an increase in void if compaction was not used, and at high AD content segregation might lead to an increase in absorption.

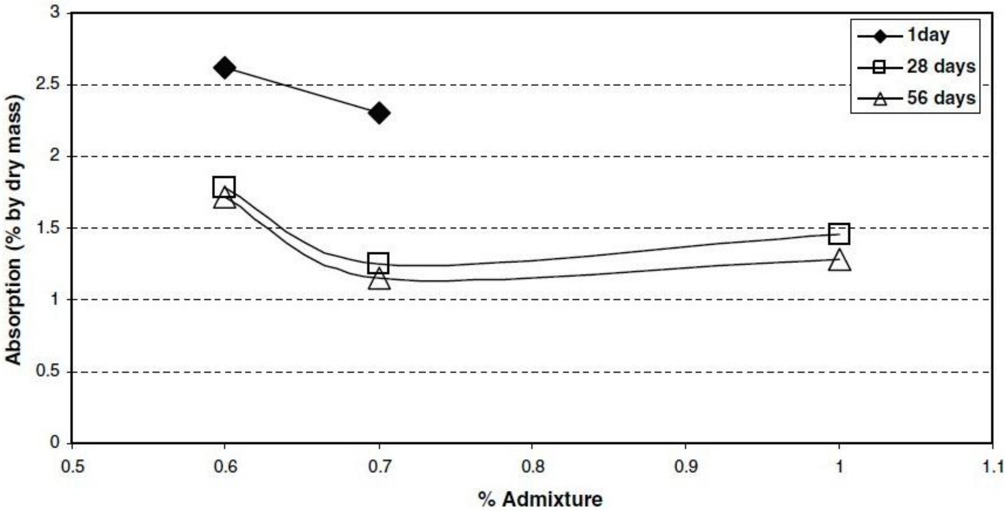

Fig 2.14: Influence of admixture dosage on absorption (Khatib 2008)

Fig 2.15 shows the influence of incorporating FA in concrete on absorption at a constant AD content of 0.7%. There is substantial decrease in absorption between 1 day curing and the other curing times (28 & 56 days). The increase in curing time from 28 to 56 days, results in further reduction but at a much slower rate compared with those obtained between 1 day and 28 days of curing. There is systematic increase in absorption with increasing FA content however, at 56 days all FA mixes including the 80% FA mix exhibited absorption values of less than or equal to 2%, which is considered to be a low water absorption. The low absorption is an indication of good compaction achieved by the concrete self-weight. The compaction is expected to be better especially in the presence of FA due to the increased workability. Generally, the absorption values for all mixes are lower than those reported in another investigation.

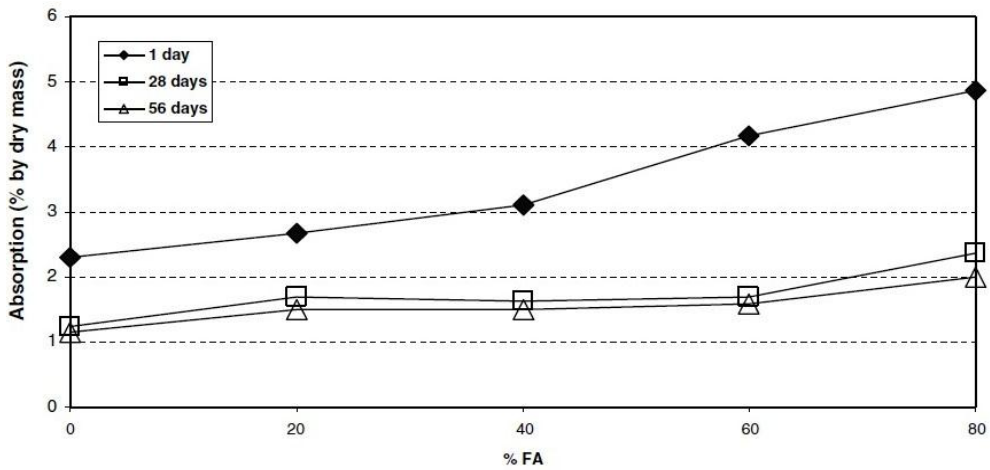

Fig 2.15: Influence of FA content on absorption, AD = 0.7 % (Khatib 2008)

2.3.3. Shrinkage

Khatib (2008) observe the drying shrinkage of SCC is similar to those of conventional concrete at the same water to cement ratio, also the shrinkage was not noticeably different from that of traditional concrete. The results were based at varying water to binder ratios.

The effect of using different amount of AD on shrinkage is shown in Fig 2.16. The results suggest that low AD dosage increases shrinkage, whereas a decrease in shrinkage occurs at high AD content. A substantial increase in shrinkage takes place during the first 28 days of hydration, after which period there is little change in shrinkage.

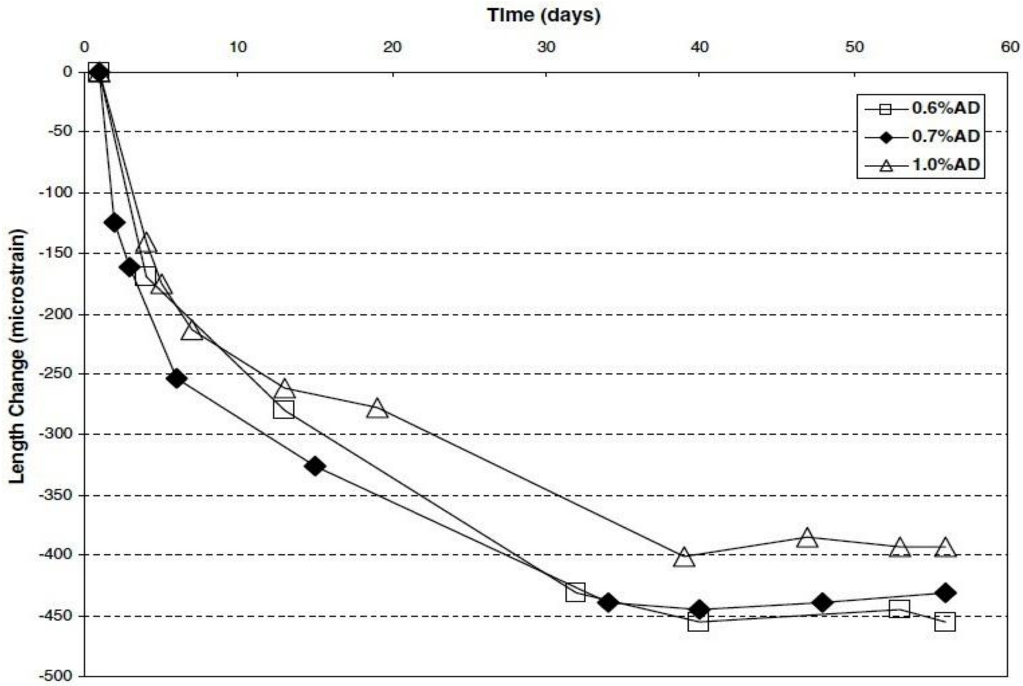

Fig 2.16: Influence of admixture dosage on shrinkage (Khatib, 2008)

Fig 2.16 displays the shrinkage profiles for the control mix M2 and for mixes containing FA (M4–M7). As for the results in Fig 2.17, most of the shrinkage occurs during the first 28 days. After that, there is little change in shrinkage up to at least 56 days. Increasing the amounts of FA results in a systematic reduction in shrinkage. At high FA content (60%) the 56 days shrinkage is reduced to half and with very high FA content (80%) the shrinkage is about one third compared with that of the control. This is better illustrated in Fig 2.18, where the 56 days shrinkage data are plotted against FA content. There is a linear relationship between FA content and shrinkage. If a straight line is fit fitted to the data an equation in the form of y = 3.5x - 425 is obtained with an R^2 = 0.98 indicating a strong correlation. The trend in shrinkage is similar to those reported elsewhere, however, and despite of the high binder content in the present investigation the shrinkage values are much lower for comparable aggregate contents. This could be attributed to the high CaO (13.4%) content of FA used in the other investigation, as opposed to 2.4% CaO used in the present work. The shrinkage values obtained for SCC are higher than those obtained for traditional vibrated concrete. Fig 2.19 correlates the 56 day shrinkage with 28 strength data. An increase in strength is associated with an increase in shrinkage.

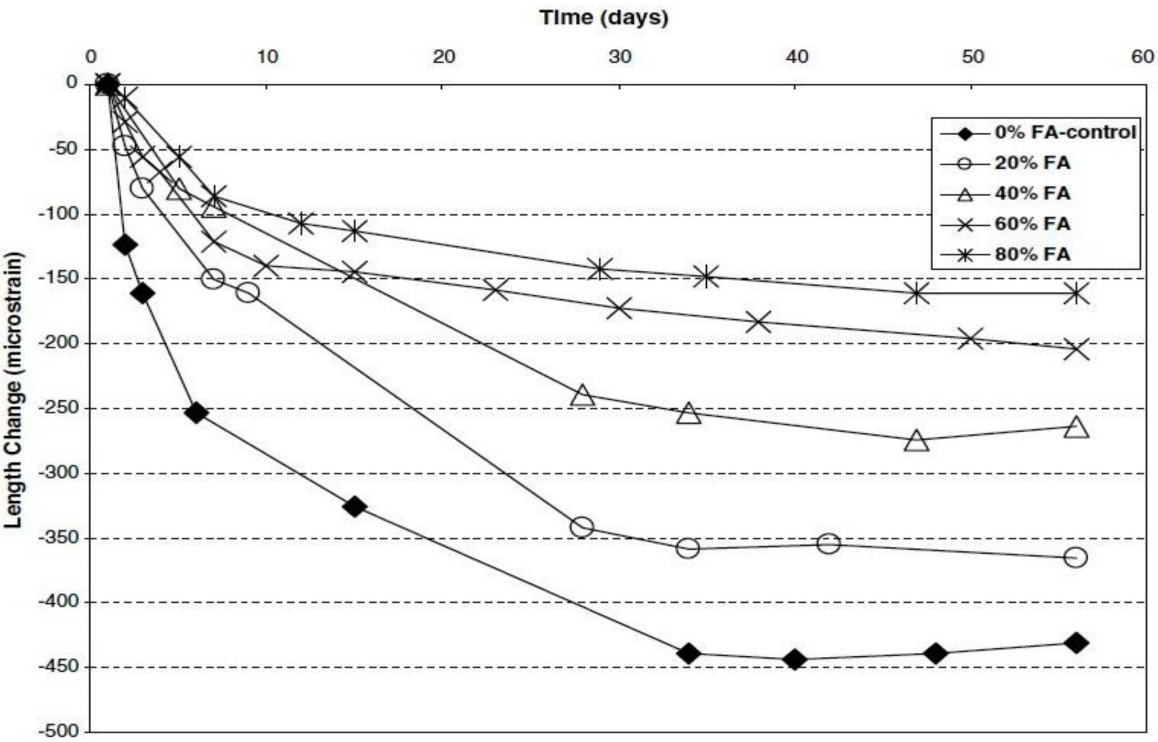

Fig 2.17: Influence of FA on shrinkage, AD = 0.7 % (Khatib, 2008)

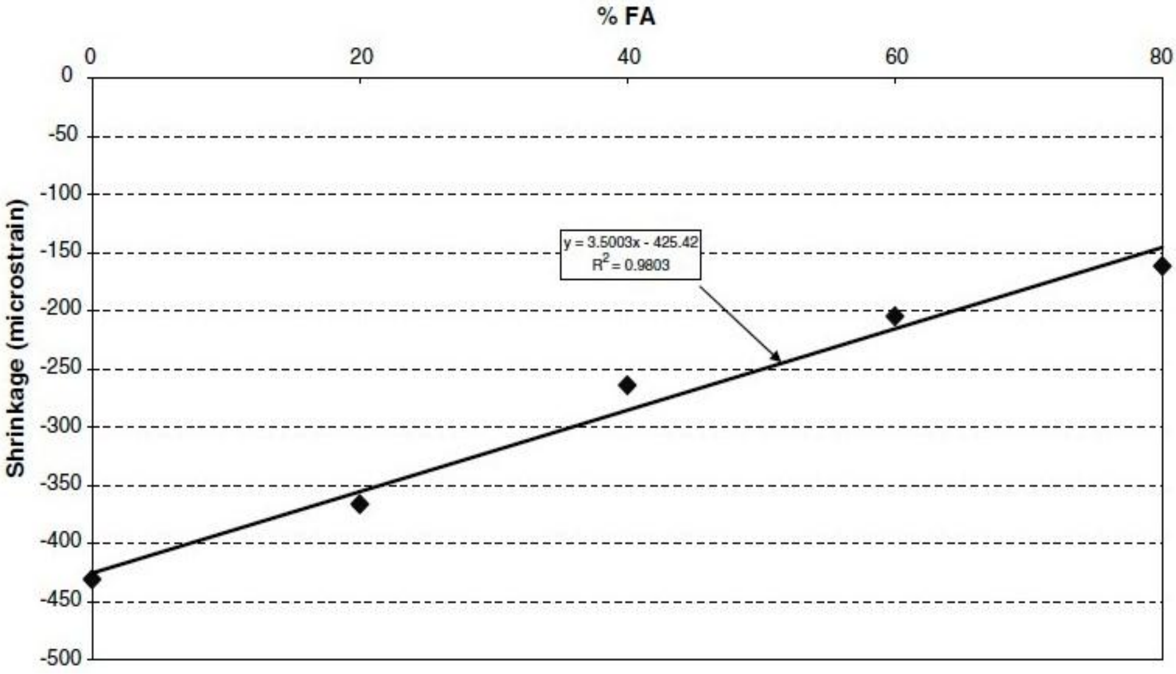

Fig 2.18: Shrinkage versus FA content at 56 days curing (Khatib, 2008)

Table 2.23: Estimation of shrinkage of SCC concrete (Khatib, 2008)

Mix	Mix ID	$\varepsilon^* = -bt / [a + t]$		
		a	**b**	**Correlation coefficient (R^2)**
M1	0% FA	7.99	525	0.99
M2	0% FA	4.06	483	0.99
M3	0% FA	7.17	444	0.99
M4	20% FA	12.10	467	0.99
M5	40% FA	13.87	350	0.99
M6	60% FA	5.70	214	0.99
M7	80% FA	8.53	188	0.99

* ε is shrinkage in microstrain.

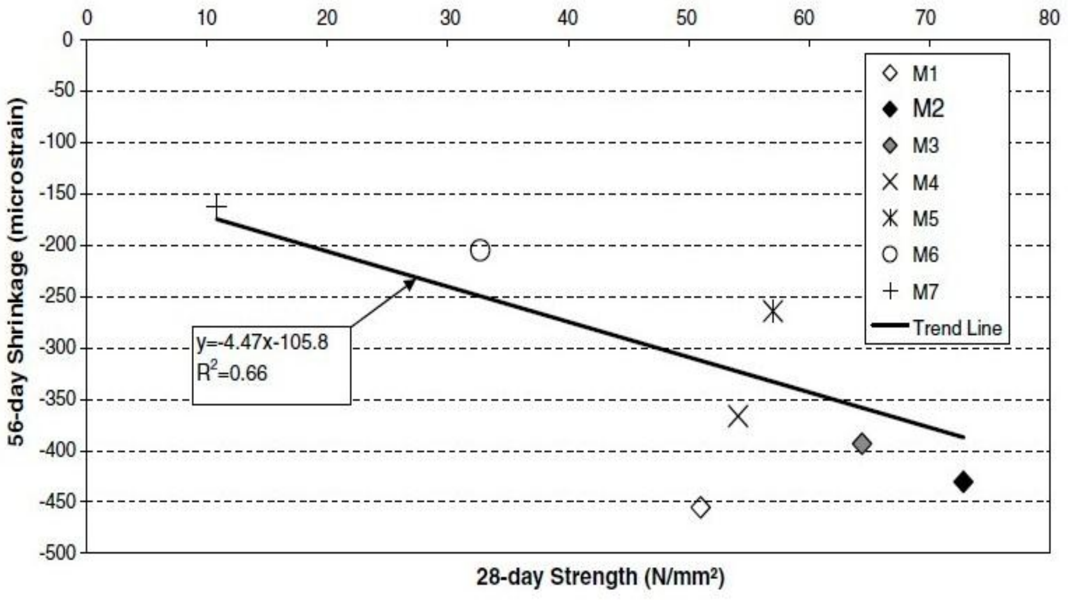

Fig 2.19: Relationship between shrinkage and strength at 56 days curing (Khatib, 2008)

Safiuddin et al. (2008) observed that drying shrinkage occurs when concrete hardens and dries out at the early age. It induces potential flow channels in the form of micro-cracks.
These cracks provide the access to deleterious agents, and thus affect the durability of concrete. The drying shrinkage of SCC does not differ very much from that of normal concrete. Several studies reported that it could be even lower in SCC. In general, the reduced coarse aggregate content and the increased amount of cementing material are expected to cause more drying shrinkage in SCC. But the porosity also affects the drying shrinkage of concrete. As the porosity is reduced in SCC, it compensates the negative effects of aggregate and binder on drying shrinkage. In addition, the drying shrinkage tends to decrease in SCC since a very small amount of free water is available in the system. Also, SCC has minimum empty voids on concrete surface that are largely responsible for drying shrinkage.

Corinaldesi, Moriconi (2002) measured shrinkage by making Prismatic specimens (100 x 100 x 500 mm) according to Italian Standard UNI 6555-73 ‘‘Hydraulic Shrinkage Determination’’. After 1 day of wet curing, the specimens were stored at constant temperature (20 ± 2ºC) and constant relative humidity (50 ± 2%) while measuring drying shrinkage at different curing times. Fig 2.20 shows the results obtained up to 180 days. A drying shrinkage of 500 µm/m can be predicted after 1 year of exposure to a relative humidity of about 50%. The effectiveness of steel fibers addition in counteracting drying shrinkage of concrete becomes evident because for a concrete with the same mixture composition without fibers, a drying shrinkage of about 800 µm/m after 6 months can be expected on the basis of well-consolidated data by Lea. Moreover, this result is further confirmed by other researchers independently of the kind of concrete, such as lightweight or fly ash or recycled aggregate and so on, as reported in the literature.

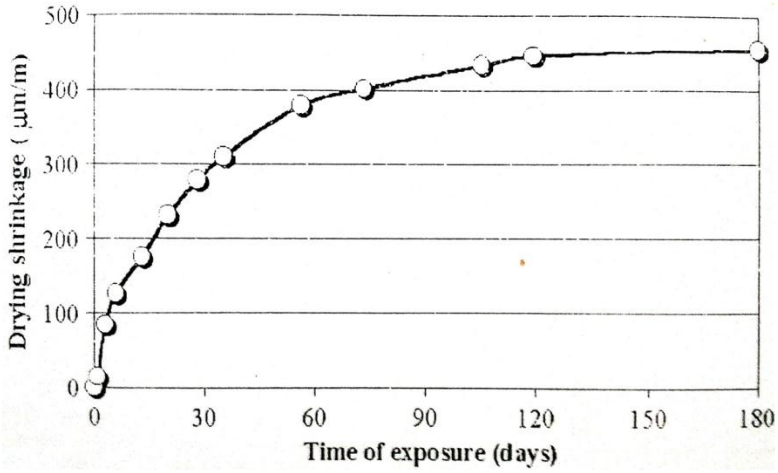

Fig 2.20: Drying shrinkage measurements up to 180 days of exposure to 50 % relative humidity (Corinaldesi, Moriconi, 2002)

2.3.4 Sorptivity

Pereira-de-oliveira et al. (2005) for the accomplishment of water absorption, by capillarity, parallelepiped samples, with 7.5 x 7.5 x 15 cm, after drying in a drying-stove, at a temperature of 100 ± 10ºC were used. The preparation of samples also included water impermeability of their lateral faces, reducing the effect of water evaporation. The test started with the registration of samples weight and, afterwards, they were placed in a recipient in contact with a height of water capable to submerge them about 5mm. After a predefined period of time, the samples were removed from the recipient to proceed to weight registration. Before the weight, the samples superficial water was removed with a wet cloth. Immediately after the weight, the samples were replaced in the recipient till reach the following time. The procedure was repeated, consecutively, until the last reading.

To evaluate the capacity of water absorption, by capillarity, of self-compacting concrete, as well as the efficiency of different mineral additions, five mixtures were produced, being a normal concrete, compacted through a needle vibrator, the reference concrete, denominated as NC, and other four mixtures with self-compacting characteristics, denominated as SCC. The self-compacting mixtures present a slump-flow test of 650 ± 50 mm and have the same cement content. To achieve the pretended workability, was used a modified carboxylates superplasticizer. The capillary absorption was carried out at 7, 14 and 28 days of age through the methodology described previously. The characteristics and properties of mixtures are presented in the Table 2.24, being used, in accordance with the addition material used, abbreviations. SCCFA for self-compacting concrete with fly ash, SCCSF for self-compacting concrete with silica fume, SCCHL for self-compacting concrete with hydraulic lime and SCCFAHL for self-compacting concrete with a mixture of fly ash and hydraulic lime.

Table 2.24: Proportion in mass of the component materials of the tested mixtures (Pereira-de-oliveira et al., 2005)

Component	**NC**	**SCCFA**	**SCCSF**	**SCCHL**	**SCCFAHL**
Cement (Kg)	1.00	1.00	1.00	1.00	1.00
Fly ash (Kg)	xx	0.15	xx	xx	0.10
Silica lime (Kg)	xx	xx	0.10	xx	xx
Hydraulic lime (Kg)	xx	xx	xx	0.20	0.10
Sand (Kg) Mf* = 2,8	0.88	1.26	1.11	1.09	1.09
Sand (Kg) Mf* = 4,5	0.88	1.26	1.11	1.09	1.09
Aggregate 6-15 (Kg)	2.75	1.98	2.29	2.32	2.32
Water/Cement (Kg/Kg)	0.40	0.40	0.55	0.48	0.48
Superplasticizer Viscocrete 3000 (%)	1.50	2.5	2.2	2.4	2.4
Water/Powdered materials (Kg/Kg)	0.40	0.35	0.36	0.33	0.33

***** *Fineness module*

The water absorption, by capillarity, in the age of 7 days demonstrates that the use of hydraulic lime as powder has a very similar effect to the silica fume, as it can be verified for the medium values presented in the Fig 2.21. The most advantageous behaviour was provided by the use of fly ash, sub-product of thermoelectric industry, more inexpensive than the silica fume. The behaviour of self-compacting concrete with a mixture of hydraulic lime with fly ash, SCCFAHL, is similar to the normal concrete compacted by vibration, NC.

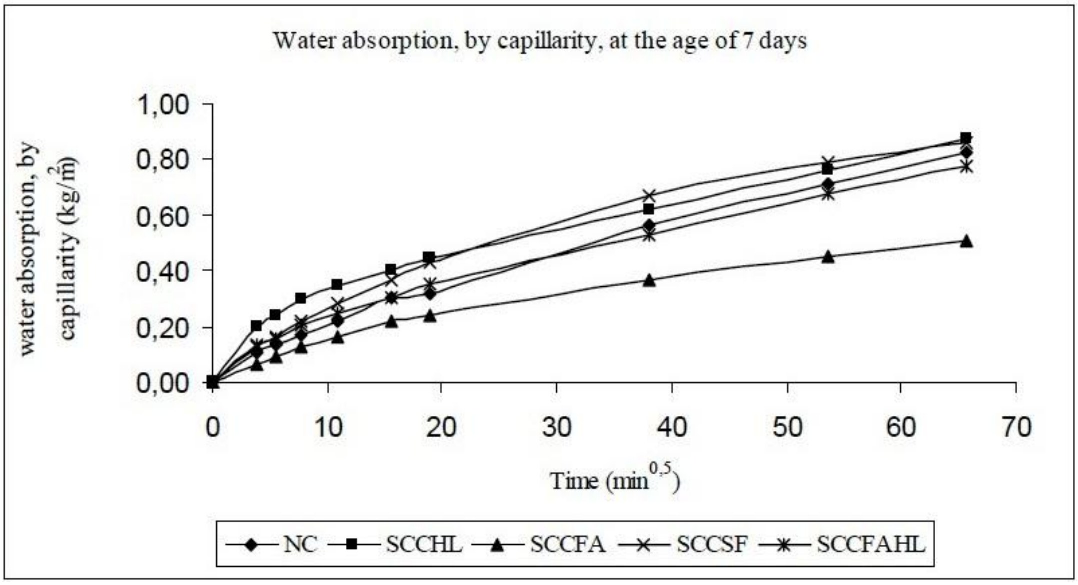

Fig 2.21: Evolution of water absorption by capillarity carried out at 7 days of age (Pereira-de-oliveira et al., 2005)

Analyzing the evolution of the water absorption, by capillarity, of mixtures, in the age of 14 days (Fig 2.22), it is noticed, with the evolution of the cement hydration, a modification on the microstructure, that hydraulic lime as the smallest efficiency as material fine to fill the capillary pores. The silica fume confers a similar behaviour to the one of the vibrated concrete, while the fly continues to develop, as thinness material of a larger efficiency, the lowest results of water absorption, by capillarity.

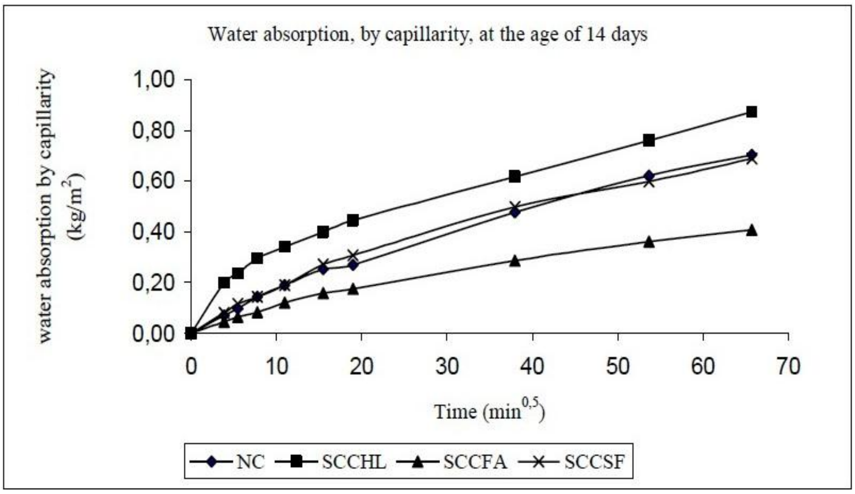

Fig 2.22: Evolution of water absorption by capillarity carried out at 14 days of age (Pereira-de-oliveira et al., 2005)

At the age of 28 days, the results are practically confirmed (Fig 2.23). However, it is verified that the addition of fly to the mixture containing hydraulic lime is quite beneficial, bringing a substantial improvement of the behaviour of SCCFAHL concrete. It is observed that this mixture, in the tests that characterizes the self-compact ability of concrete, presented results that express a smaller filling capacity and fluidity that the other mixtures.

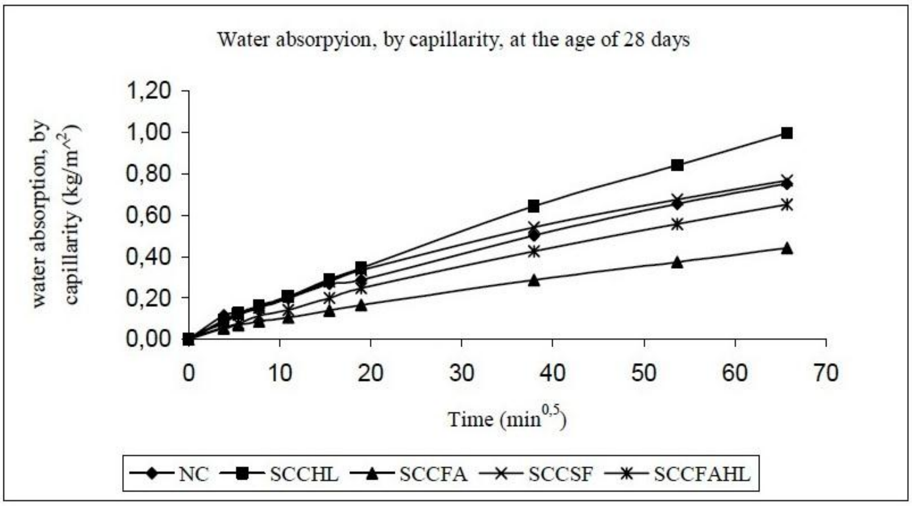

Fig 2.23: Evolution of water absorption by capillarity carried out at 28 days of age (Pereira-de-oliveira et al., 2005)

In this experimental program the silica fume, material considered less inexpensive, when compared to others here employed, conferred to the SCCSF mixture similar behaviour to the one of the vibrated concrete.

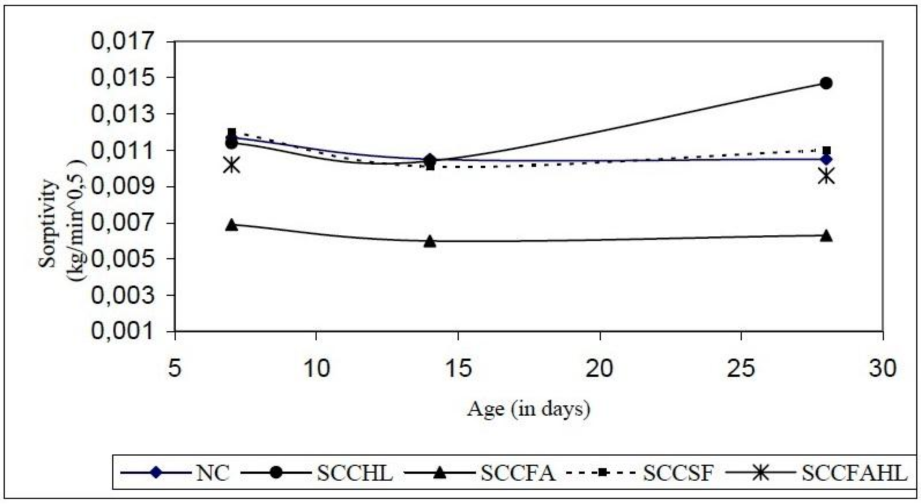

Fig 2.24: Sorptivity coefficient versus age of different self-compacting concrete (Pereira-de-oliveira et al., 2005)

Therefore, it can be inferred that the improvement of the characteristics that confer durability to a hardened concrete, in matter the water absorption by capillarity, it is obtained with the employment of a self-compacting concrete, in which is used an addition of the type fly ash. The behaviour of self-compacting concretes, in relation to the water absorption by capillarity, one of the parameters used to foresee durability, it is equal or better than the one of a normal concrete compacted by vibration. The addition of the fly ash, which was used in this work, conferred a better performance to the self-compacting concrete appraised through the water absorption by capillarity. This same addition mixed with hydraulic lime also improved the concrete performance, at the age of 28 days. The silica fume, the less inexpensive of the additions, conferred to the self-compacting concrete a similar behaviour to the one of normal concrete compacted by vibration.

Turk et al. (2007) observed that the Sorptivity coefficient can be determined by means of simple test allowing one face of concrete specimen be in contact with water and the mass (non-destructive) or height (destructive) of water absorbed by capillary suction is measured at predefined intervals. Water absorption tests were carried out to determine the Sorptivity coefficient of concrete specimens, which were preconditioned in oven at 105º C for 24 hours and then cooled down within desiccators for 24 hours to achieve a constant moisture level. Then 4 sides of concrete specimen were sealed by electrician tape to avoid evaporative effect as well to maintain uniaxial water flow during the test and opposite faces were left open.

One face of the specimen was in contact with water whilst the water absorption at predefined intervals was measured with a scale of 0.1 g readability. The Sorptivity coefficient can be calculated by the following expressions.

$$S = (Q/A) / \sqrt{T}$$

Where S is the Sorptivity (cm/min$^{1/2}$), Q is the mass of water absorbed in kg, A is the surface area in contact with water in cm^2 and t is the time in minutes.

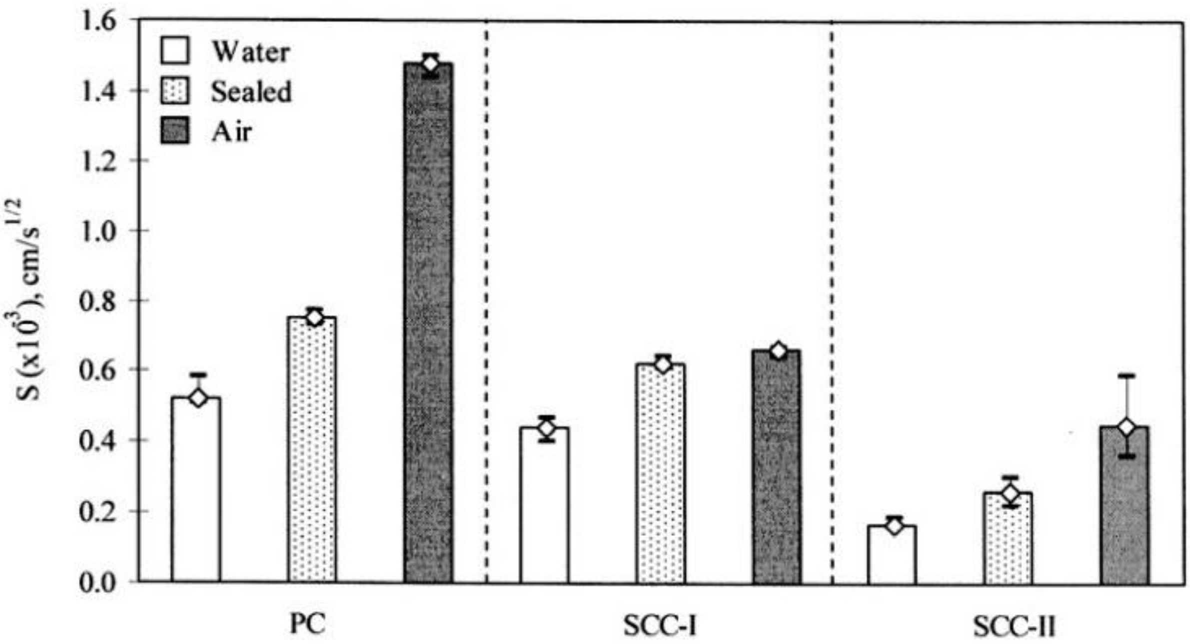

Fig 2.25: Sorptivity values of self-compacting concrete in different curing conditions (Turk et al., 2007)

The results of the Sorptivity test are given in Fig 2.25 on the basis of curing conditions and concrete types. It is indicated that the SCC-II gave the lower sorptivityvalues followed br SCC-I and then the PC in all curing conditions. The highest Sorptivity value (1.5 ($x10^{-3}$) $cm/s^{1/2}$) was obtained from PC cured in air, whislt the lowest Sorptivity value (0.2 ($x10^{-3}$) $cm/s^{1/2}$) was obtained from SCC-II cured in water. It can be suggested, therefore that a proper curing as well as a pozzolanic admixture such as FA or SF as cement component can be enhance the resistivity of concretes against water absorption significantly.

Bentz et al. (2001) proposed a method for calculating Sorptivity. In this materials were obtained from the Rhode Island and Missouri Departments of Transportation during the summer 2000 construction season. The specimens received from the Rhode Island DOT were cores from small slabs (610 mm x 610 mm x 914 mm deep or 2 ft x 2 ft by 3 ft). The slabs were prepared by pumping the concrete into the molds. The slabs were then field cured and the cores were removed after 28 days. The cores were 368 mm (14.5 in) in length and 100 mm (4 in) in diameter. The specimens received from the Missouri DOT were cores from actual pavement slabs, not from separately cast specimens. These were taken from Route 65 in Benton County and from Route 13 in Henry County. The cores were either from the driving lane or the passing lane and were all from the northbound direction of the road. All specimens were received wrapped in plastic bags and were immediately stored in limewater upon reception by NIST until testing time. A 50 mm (2 in) slice was cut from each specimen for testing Sorptivity. Precautions were taken to always use the top surface of the pavement. The compositions of the three concretes are given in Table 2.25

Sorptivity Testing

Water ingress into a non-saturated concrete structure is due to sorption, driven by the capillary forces. If the water is on top of the concrete surface, gravity also will play a role in the water penetration. To measure the sorption coefficient of concrete, a new test proposed by NIST to ASTM for standardization was used. The method is similar to that recently published as a RILEM recommendation. The principle of the method is that a concrete specimen has one surface in contact with water while the others are sealed. The proposed standard test allows either the top surface to be in contact (simulation of water on a pavement or bridge deck) or the bottom surface (substrate in contact with water). The first case is referred to as ponding sorption and the second as capillary sorption. As the most common case of water sorption in a pavement is ponding, all the tests for this paper were done using the ponding method.

Table 2.25: Compositions of concrete (Bentz et al., 2001)

Materials	**Rhode Island**	**Missouri Route 65**	**Missouri Route 13**
Cement [Kg/m^3]	417	290	342
Water/Cement ratio	0.39	0.36	0.35
Aggregates			
Sand type Amount [Kg/m^3]	Concrete 681	River sand 586	Class A sand 616
Coarse Aggregates Amount [Kg/ m^3]	¾ and pea stones 1054	Limestone 1069	Crushed limestone 992
Admixtures type Amount [L/ m^3]	Corrosion inhibitor 15	Air entrainer 73	None
Suppl. Cementitious Materials type Amount [Kg/ m^3]	None	Fly Ash 51	None

The ponding sorption test consists of pre-conditioning the specimen by vacuum impregnation with water, followed by 3 days or 7 days in an environmental chamber with a controlled temperature and RH of 50 °C and 80 %, respectively. After this treatment, the specimen is placed in a closed container for 14 days and the RH is measured regularly. When the RH is constant, it signifies that the water in the specimen is evenly distributed throughout and that the specimen is in equilibrium with this measured RH. Several tests have indicated that the equilibrium RH is obtained in about 10 days. We selected 14 days to ensure that equilibrium was reached with all of the concretes. With this preconditioning regime, the specimen internal RH is typically about 60 %. The concrete specimens were 50 mm (2 in) thick disks sliced from the received cores. The sides were covered with duct tape before the pre-conditioning. To measure the ponding sorption, some duct tape was used to form a pool as shown in Fig 2.26 A two-component epoxy caulk was used to seal the space between the tape and the concrete. Plastic wrap secured with a rubber band was used to seal the bottom surface.

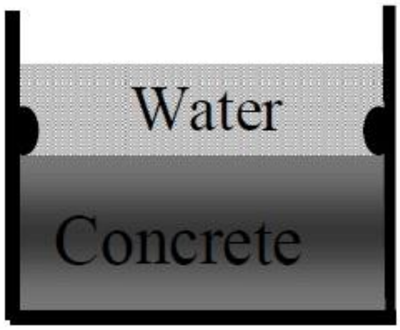

Fig 2.26: Schematic of ponding sorption test (Bentz et al., 2001)

The mass of the specimen was regularly measured after the water on the top was poured out and the top surface was patted dry. To determine the sorption coefficient, the mass gain divided by the surface area of the top surface is plotted versus the exposure time. The sorption coefficients are defined as shown in the following equation:

$$W/(ñA) = I \sqrt{t} + I_0$$

Where all terms are defined in the Nomenclature section above and

I = early age sorption coefficient [$m/s^{1/2}$] if 1 min < t < 7 h

Later age sorption coefficient [$m/s^{1/2}$] if t > 1 day

I_0 = initial sorption (m)

ñ = density of water (kg/m^3)

Fig 2.27 shows these two slopes or sorption coefficients. Two slopes have been observed for the results obtained from a wide variety of concretes and mortars10. The later age sorption coefficient is usually attributed to other phenomena besides the capillary forces alone, such as filling of the larger pores and air voids.

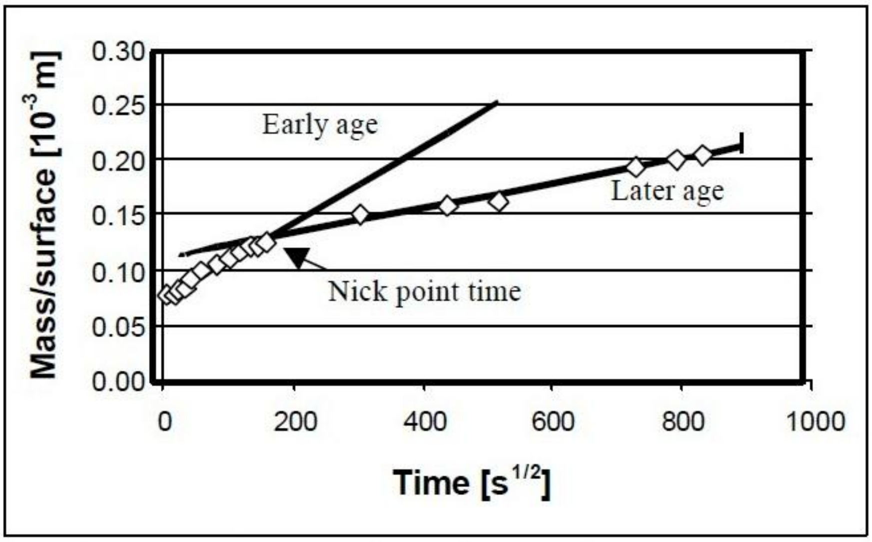

Fig 2.27: Calculation of the sorption coefficient (Bentz et al., 2001)

In the laboratory, Sorptivity testing is generally performed at room temperature (25ºC). In the modelling, these sorptivities are adjusted for the predicted concrete surface temperature based on the characteristics of water (surface tension, ó, and dynamic viscosity, ç) as a function of temperature. Hall has indicated that Sorptivity should generally scale as (ó/ç) 0.5. Additionally, since the laboratory sorptivities are typically measured on concretes with an internal RH of about 60 %, the sorptivities are further adjusted for the RH of the environment prior to the wetting event, using linear interpolation and assuming a Sorptivity of zero for fully saturated concrete (RH = 100 %).

2.3.5. Sulfate Resistance

Irassar (2009) studied that the External sulfate attack (ESA) to cementitious matrix is a complex process that involves the movement of sulfate ions through the pores by means of different mechanisms of transportation and the interaction of aggressive solution with some compounds of cement paste (AFm phases, hydrogarnet phases, unhydrated alumina phases and CH) to form expansive compounds (ettringite and gypsum) that produce cracking, strength loss and softening. The most important factor to prevent external sulfate attack is to reduce the permeability of the concrete (low water/cement ratio, high cement content, well compacted and well cured). In terms of cement composition, C_3A is the main compound involving sulfate resistance, whereas C_4AF, an alumina bearing phase, and CH released from silicates hydration can also affect the sulfate resistance of low C_3A Portland cements.

In an acidic sulfate environment (pH<7), gypsum formation causes local expansion, spalling and strength retrogression. The acid media contribute to the gradual removal of CH from the paste until complete depletion, which promotes decomposition of C–S–H that causes loss of adhesion and stiffness. As for $MgSO_4$ attack, Mg^{2+} and SO_4^{2-} react with CH to produce gypsum and brucite in the surface forming a double layer. The reduction of alkalinity due to $Mg(OH)_2$ insolubility results in more Ca^{2+} release from C–S–H, increasing the gypsum formation and, finally, the decomposition of C–S–H to non cementitious MSH. In a wet environment, thaumasite is readily formed by ESA when calcium silicate-ions and carbonate ions or atmospheric CO_2 dissolved in water are present in the pore solution of cement paste. Therefore, thaumasite sulfate attack (TSA) may occur in mortar or concrete containing limestone ($CO_3^{\ 2-}$), as filler or aggregate, exposed to sulfate solution ($SO_4^{\ 2-}$) when the attack causes the disintegration of C–S–H in cement paste (SiO_3) in the presence of Ca^{2+}. This deterioration can proceed faster in cold environments (below15 °C), and it is particularly more deleterious when sulfates are associated with the Mg^{2+} and low pH as both contribute to the decomposition of C–S–H. This attack causes a gradual softening of the surface of concrete as well as a gradual inwards progression. Finally, cement paste is transformed into a non-cohesive mass leading to the loss of particles. Thaumasite could be formed by two different but closely related routes. These are the direct route from C–S–H formed during hydration of silicate phases (C_3S and C_2S), and the woodfordite route from ettringite produced during hydration of the alumina bearing phases (C_3A and C_4AF) in the presence of calcium sulfate. The reasons and processes in the first transformation of tetrahedral SiO^-_4 into octahedral SiO_6^- of thaumasite still remain unknown. In the second route, it is believed that the evolution of ettringite into thaumasite takes place through the discontinuous solid solution where ettringite crystal incorporates Si^{4+} in its structure, substituting Al^{3+} ions in the presence of CO_3^{2-}. Hence, all main phases of hydrated cement paste can slowly convert to non-binder thaumasite. The formation of thaumasite through a solution mechanism. For this mechanism, sulfate ions ingress into pore solution and reactwith alumina, calcium, carbonate or bicarbonates and silica ions to form ettringite, gypsum or thaumasite depending on concentrations of ions, relative solubility of the competing species and the stability of precipitates. For low permeable concrete (low w/c, well curing, no cracking), ESA occurs very slowly due to null or limited ion transport from solution to paste. However, for permeable concrete in contact with $CO_3^{\ 2-}$,the use of sulfate-resisting Portland cements (SRPC, low C_3A cement, Type V) does not necessarily prevent the formation of thaumasite, because it can be formed from C–S–H present in the hardened paste. In this case, it is suggested that the rate of attack increases when coupled with other mechanisms (acid attack, magnesium attack or extreme carbonation of paste) that produce the decomposition of C–S–H due to the reduction of the alkaline environment needed for its preservation. A secondary cause that could increase vulnerability of SRPC in the sulfate environment is the increase of C_3S/C_2S in cement composition.

The progress of ESA requires the presence of aggressive ions in solution, the transport of these ions into the cementitious matrix and the reaction with some hydrated cement products to produce expansion or degradation. This process starts on the surface and madvances inwards into the specimens as the exposure time increases. From field and laboratory observations, we inferred that the magnitude of TSA depends on the combination of several factors: wet conditions, low temperatures, exposure to sulfates associated with the magnesium cation, the prior formation of conventional sulfate attack products and the presence of at least between 10% and 35% of $CaCO_3$ by mass of the cement. These factors can be combined as follows:

- aggressiveness of sulfate environment (sulfate concentration, magnesium concentration, pH, temperature)
- composition of mixtures (w/c ratio, curing) that contribute to water transport
- characteristic cementitious materials (C_3A content, limestone filler content, C_3S/C_2S ratio).

According to the Durability Guide of ACI 201 Committee, the aggressiveness of sulfate environments is classified into four types based on the concentration of $SO_4^{\ 2-}$ (g/l) and it only suggests that groundwater containing $MgSO_4$ is more aggressive. In the European

Concrete Standard EN 206, exposure to chemical attack is classified into slightly, moderately or highly aggressive classes according to the $SO_4{}^{2-}$, Mg^{2+}, NH^{4+} concentration and pH. This classification is based on static water and temperatures between 5 and 25 °C. However, the temperature plays an important role in TSA; when the temperature drops below 15 °C, formation of thaumasite can arise and deterioration increases at a more rapidly rate in cold

Environments the control of pH can change the predominant phases of attack, especially gypsum formation by CH depletion. Sodium and magnesium sulfate solutions are neutral, but the evolution of pH in the solution-specimen system is quite different. In Na_2SO_4 solution, the pH increases rapidly (near to 12) when specimens are immersed in them due to CH dissolution, whereas $MgSO_4$ solution may be buffered at pH near 7 due to the insoluble nature of the $Mg(OH)_2$ produced. In reviewed tests, this factor is controlled by renewing the solution every one-four months or by daily or weekly pH control. Also, there is no information in some tests procedures. Another condition to avoid this pH change in solution is to increase largely the volume of solution/volume of the specimen. These test conditions results can be divided into sulfate solution with or without magnesium ions and temperature of storage lower or higher than 15 °C. Analyzing ions concentration according to the ACI 201 or EN 206.

- Na_2SO_4 solution at temperature 15 °C: In all tests, sulfate content is higher than the limit for C3 Class of ACI 201 (N10 g/l $SO_4{}^{2-}$) and XA3 Class of EN 206 (6 g/l $SO_4{}^{2-}$).
- $MgSO_4$ solution at temperature 15 °C: Sulfate concentration allows classifying all solutions as C3 Class of ACI 201 and the concentration of $SO_4{}^{2-}$and Mg^{2+} (N3 g/l) are above the limit of XA3 Class of EN 206.
- Na_2SO_4 solution at temperature 15 °C: Most of tested solutions are C3 Class, According to EN 206 classification, all exposures are XA3 Class.
- $MgSO_4$ solution at temperature 15 °C: a wide range of concentrations are used for these conditions. Most solutions are C3, two are C2 and one is C1 class of ACI 201;whereasmost of test solutions are classified as XA3 Class of EN206, two are in the upper threshold of XA2 Class (3 g/l $SO_4{}^{2-}$).

Most test solutions used provided a highly aggressive environment and, in this case, concrete codes required the design of a concrete mixture with a maximum w/c, compositional restriction in Portland cement, a minimum specified compressive strength and an appropriated period of curing.

For ESA, the formation of compounds into the matrix induces a change in porosity, microcracking, expansion, tensile, flexural or compressive strength loss, spalling, mass loss and severe degradation on the surface. For the same aggressiveness of the environment and w/c, the evolution of deformation, mass loss or mechanical properties depend on constitution of specimens (paste, mortar, and concrete), size of specimens, and type of sulfate used. For example, the expansion of specimens exposed to Na_2SO_4 solution is higher than that of mortar specimens exposed to $MgSO_4$ with a similar solution concentration of sulfate ions and specimens size. On the other hand, loss of compressive strength is high in mortars exposed to $MgSO_4$. For this reason, it is very complex to compare data obtained from different studies.
To assess the sulfate performance of the cementitious system, most investigations have included a description of the visual appearance of specimens. Several techniques such as visual rating, photographical records, and proportion of surface or edge of specimens affected have been used for this purpose. At the first stages of attack, pores are filled with deposition of sulfate attack products that cause no visible deterioration and white powdery coating is sometimes detected. Regardless of exposure solutions, the first sign of attack was the deterioration the specimen corners followed by extensive cracking along the edges and, finally, spalling and disintegration on the specimen surfaces. Summarizes the visual rating used to classify surface deterioration of different research papers analyzed. The degree of surface deterioration progress in time and results with more than four months of exposure are only included in the conceptual graph. For this degradation indicator conceptual graphic including most data reported of cementitious materials exposed to different environments, with different proportions of mixture (effective w/c) and cementitious materials of different composition (C3A, LF content).

Najimi et al., (2011) used copper slag waste as SCM. Unlike the reported researches having high SiO_2 (25–40%) and low CaO (0.6–10%) contents, the utilized copper slag has lower SiO_2 and higher CaO amounts respectively about 9.5% and 22%. Considering the availability of sufficient lime quantity required for hydration and strengthening (at early ages), this especial type of copper slag may be considered as a reactive cementitious material. The summation of silica, alumina and iron oxide in the copper slag is 71.4%, slightly exceeding the 70% limit for Class N raw and calcined natural pozzolans, according to ASTM C618. The strength activity index of copper slag was measured based on ASTM C618. The strength activity of copper slag is slightly higher than the natural pozzolan and fly ash requirements of 75% according to ASTM C618. Besides, as a well-known pozzolanic activity measurement, thermo-gravimetric analysis was performed on copper slag to evaluate calcium hydroxide consumption. This method is based on the thermal decomposition of crystalline calcium hydroxide in a temperature range of 400–500ºC to calcium oxide and water. The pozzolanic activity were measured by combining 50% copper slag and 50% calcium hydroxide powder in presence of enough water for pozzolanic reactions. In order to investigate the effects of sulfate attack, of each mixture, three concrete prisms (75 x 75 x 285 mm) and 33 concrete cubes (100 x 100 x 100 mm) were prepared. From them, nine cubes were used for determining the compressive strength of concrete continuously immersed in water (normal condition), while 24 cubes and 3 prisms were applied for measuring the compressive strength and length expansion of concretes immersed in sulfate solution (sulfate attack condition), respectively. Especial curing and exposure regime were adopted to study the sulfate attack on the concrete. Concrete cubes and prism specimens were cured in water for 7 days and after that immersed in the sulfate solution having 50 g per liter of Na_2SO_4

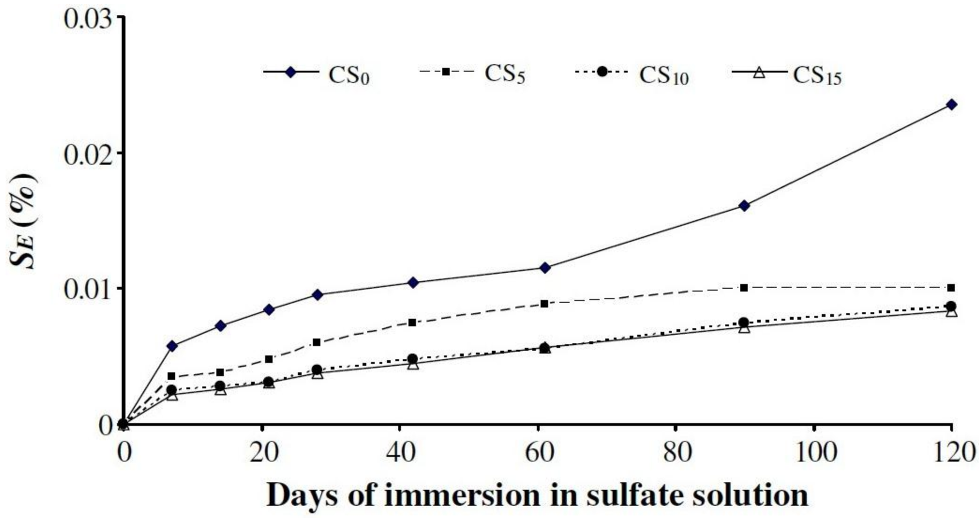

Fig 2.28: Expansion in sulfate solution versus age (Najimi et al., 2011)

To study the influence of copper slag replacement on the sulfate expansion, the length of concrete prisms immersed in sulfate solution was measured during the immersion time. The expansion due to sulfate attack (S_E) is determined by using the following equation adopted from ASTM C1012.

$$S_E = [(L_t - L_0)/L_0 \times 100$$

where L_t is the length of specimen at time t after immersion in sulfate solution and L_0 is the initial length before immersion in sulfate. SE curves of specimens are illustrated in Fig 2.28 for CS_0, CS_5, CS_{10} and CS_{15} containing 0%, 5%, 10% and 15% of copper slag respectively. The expansions of CS_5, CS_{10} and CS_{15} were 76.5%, 48.7% and 49.6% of CS0 expansion after 61 days immersion, whereas after 120 days immersion these values decreased to 42.6%, 36.6% and 35.3% respectively. These observations emphasize that concretes containing copper slag (CS_5, CS_{10} and CS_{15}) showed better performance than control concrete (CS_0), in particular by proceeding the sulfate solution exposure time. Besides, by increasing the amount of copper slag from 5% to 10%, the observed expansion decreased, while the expansions of samples containing 10% and 15% of copper slag were almost similar.

Safiuddin et al. (2008) concluded that Sulfate attack causes concrete deterioration by chemical and/or physical reactions. In this phenomenon, sulfate ions penetrating from soil or ground water or already being in concrete mainly react with the aluminate phase of 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.

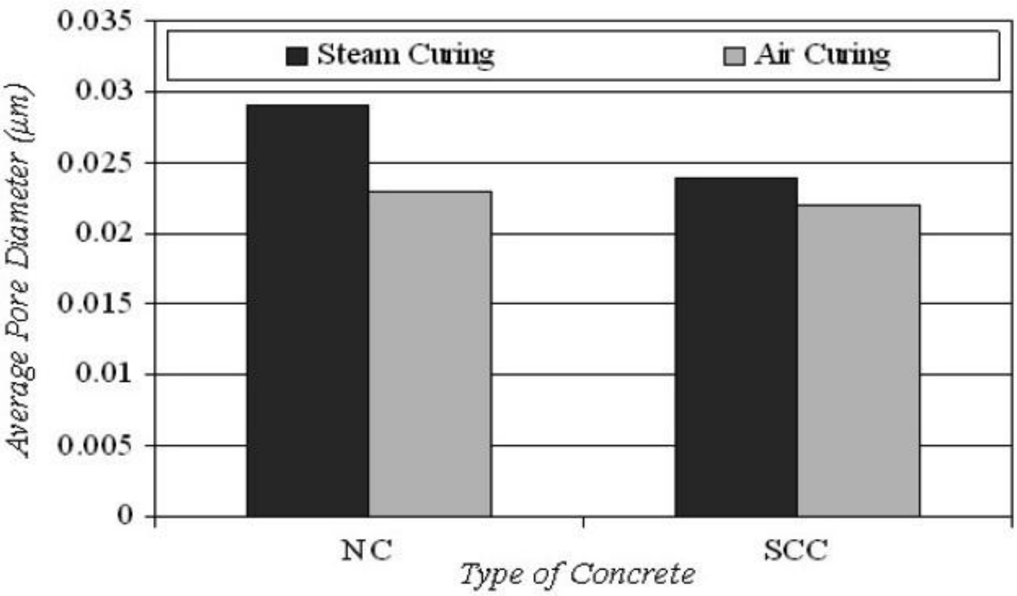

Fig 2.29: Sulfate Resistance of SCC (Safiuddin et al., 2008)

These studies indicate that the ingress of sulfate ions into SCC is impeded due to its reduced porosity and decreased transport properties.

Dinakar et al. (2008) studied the chemical resistance of concrete through chemical attack by immersing them in an acid solution. After 90 days period of curing the specimens were removed from the curing tank and their surfaces were cleaned with a soft nylon brush to remove weak reaction products and loose materials from the specimen. The initial weights were measured and the specimens were identified with numbered plastic tokens that were tied around them. The specimens were immersed in 3% H_2SO_4 solution and the pH (~4) was maintained constant throughout. The solution was replaced at regular intervals to maintain constant concentration throughout the test period. The mass of specimens were measured at regular intervals up to 90 days, and the mass losses were determined.

Table 2.26: Weight loss in acid attack (Dinakar et al., 2008)

No	**Concrete name**	**Weight loss in acid attack (90 days)**
1.	NC20 .	-25.73
2.	SCC558	-4.31
3.	NC30	-15.19
4.	SCC557	-1.37
5.	SCC757	-11.09
6.	NC60	-23.12
7.	SCC555	-23.26
8.	SCC655	-38.90
9.	NC90	-24.16
10.	SCC553	-37.86
11.	SCC530	-57.29
12.	NC100	-23.35

The results of acid attack studies in terms of the weight loss after 90 days for all the concretes are reported in Table 2.26. It can be seen that in the concretes of lower strength (20 and 30 MPa) the weight loss decreased with increasing percentage of fly ash replacement. But concretes of higher strengths show a marginally higher weight loss particularly at higher exposure times. This was probably due to the fact that the acid attack as is known is primarily related to the actual cement contents in these concretes. In view of this the weight loss was studied in terms of the cement contents and the replacement percentages at this stage. The relationship between weight loss at 90 days and cement content is shown in Fig 2.30.

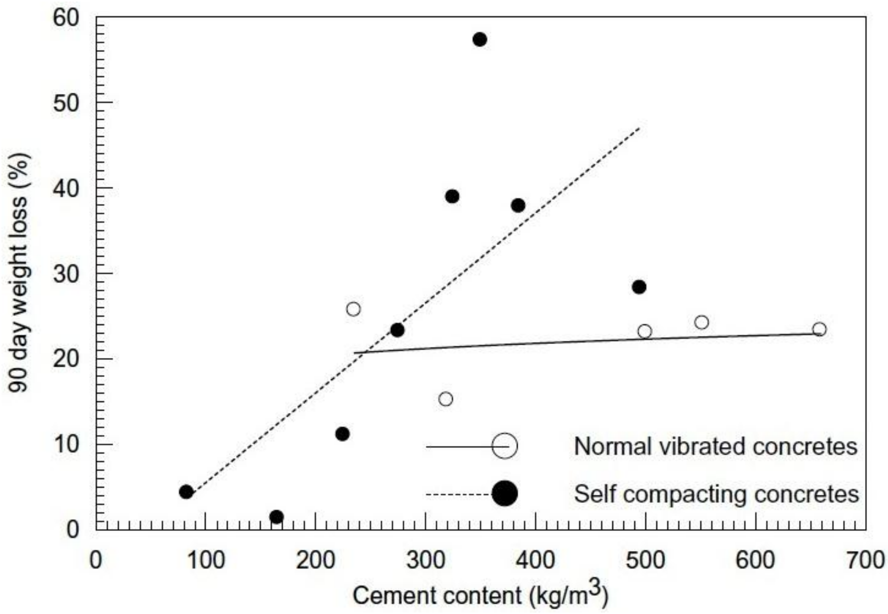

Fig 2.30: Weight loss with cement content in acid attack test (Dinakar et al., 2008)

This shows that the weight loss due to acid attack increased up to a cement content of 400 kg/m^3, after which there was a marginal decrease. It can also be seen that both normal concretes (the experimental points with unfilled symbols) as well as the Self-compacting fly ash concretes (the experimental point with filling) have all been following the same trend. Obviously, the low strength concretes with low amount of cement show better resistance against acid attack. This could be due to the low amount of reaction compounds like $Ca(OH)_2$ at lower level of cement content for deterioration process.

CHAPTER 3: EXPERIMENTAL PROGRAMME

3.1. GENERAL

The aim of the experimental program is to compare the properties of Self-compacting concrete made with and without fly ash and silica fume, used as supplementary cementing material. The basic tests carried out on concrete samples are discussed in this chapter, followed by a brief description about mix deign and curing procedure adopted. At the end, the various tests conducted on the specimens are discussed.

3.2. MATERIAL USED

3.2.1. Cement

Cement is a fine, grey powder. It is mixed with water and materials such as sand, gravel, and crushed stone to make concrete. The cement and water form a paste that binds the other materials together as the concrete hardens. The ordinary cement contains two basic ingredients namely argillaceous and calcareous. In argillaceous materials clay predominates and in calcareous materials calcium carbonate predominates. Basic composition of cement is shown in Table 3.1.

Table 3.1: Composition limits of Portland cement.

INGREDIENT	% CONTENT
CaO (Lime)	60-67
SiO_2 (Silica)	17-25
Al_2O_3 (Alumina)	3-8
$Fe_2\,O_3$ (Iron Oxide)	0.5-6
MgO (Magnesia)	0.1-4
Alkalies	0.4-1.3
Sulphur	1-3

Grade 43 Ultra Tech cement was used for casting cubes and cylinders for all concrete mixes. The cement was of uniform colour i.e. grey with a light greenish shade and was free from any hard lumps. Summary of the various tests conducted on cement are as under given below in Table 3.2

Table 3.2: Physical Properties of Cement

S.No.	Characteristics	Values Obtained	Standard values
1.	Normal Consistency	33%	-
2.	Initial Setting time	48 min	Not be less than 30 minutes
3.	Final Setting time	240 min	Not be greater than 600 minutes.
4.	Fineness	4.8 %	<10
5.	Specific gravity	3.09	-
Compressive strength:- Cement : Sand (1:3)			
1.	3 days	24.5 N/mm^2	27 N/mm^2
2	7 days	38 N/mm^2	41 N/mm^2
3.	28 days	45 N/mm^2	43 N/mm^2

3.2.2. Fine Aggregates

The sand used for the experimental programme was locally procured and conformed to Indian Standard Specifications IS: 383-1970. The sand was first sieved through 4.75 mm sieve to remove any particles greater than 4.75 mm and then was washed to remove the dust. Properties of the fine aggregate used in the experimental work are tabulated in Table 3.3. The aggregates were sieved through a set of sieves to obtain sieve analysis and the same is presented in Table 3.4. The fine aggregates belonged to grading zone III.

Table 3.3: Physical Properties of fine aggregates

Sr. No.	Characteristics	Value
1.	Specific gravity	2.46
2.	Bulk density	1.4 kg/m^3
3.	Fineness modulus	2.56 m^2/g
4.	Water absorption	0.85 %
5.	Grading Zone (Based on percentage passing 0.60 mm)	Zone III

Table 3.4: Sieve analysis of fine aggregates

Sr. No.	Sieve Size	Mass retained	Percentage Retained	Cumulative Percentage Retained	Percent Passing
1	4.75mm	4.0 g	0.4	0.4	99.6
2	2.36 mm	75.0 g	7.50	7.90	92.1
3	1.18 mm	178.0 g	17.8	25.70	74.3
4	600µm	220.0 g	22.0	47.70	52.3
5	300µm	274.0 g	27.4	75.10	24.9
6	150µm	246.5 g	24.65	99.75	0.25
7				∑=256.55	

Total weight taken = 1000gm

Fineness Modulus of sand = 2.56

3.2.3 Coarse aggregate

The material which is retained on IS sieve no. 4.75 is termed as a coarse aggregate. The crushed stone is generally used as a coarse aggregate. The nature of work decides the maximum size of the coarse aggregate. Locally available coarse aggregate having the maximum size of 10 mm was used in our work. The aggregates were washed to remove dust and dirt and were dried to surface dry condition. The aggregates were tested as per IS: 383-1970. The results of various tests conducted on coarse aggregate are given in Table 3.5 and Table 3.6 shows the sieve analysis results.

Table 3.5: Physical Properties of Coarse Aggregates (10 mm)

Sr. No	**Characteristics**	**Value**
1	Type	Crushed
2	Specific Gravity	2.66
3	Total Water Absorption	0.56
4	Fineness Modulus	6.83

Table 3.6: Sieve Analysis of Coarse Aggregates (10mm)

Sr. No.	**Sieve Size**	**Mass Retained (gm)**	**Percentage Retained**	**Cumulative Percentage Retained**	**Percent Passing**
1	20 mm	0	0	0	100
2	10 mm	2516	83.89	83.87	16.13
3	4.75 mm	474	15.8	99.67	0.33
4	PAN	10	0.33	∑= 183.54	

Total weight taken = 3Kg

FM of 10 mm Coarse aggregate = [183.54+500] / 100 = 6.83.

3.2.4 Water

Generally, water that is suitable for drinking is satisfactory for use in concrete. Water from lakes and streams that contain marine life also usually is suitable. When water is obtained from sources mentioned above, no sampling is necessary. When it is suspected that water may contain sewage, mine water, or wastes from industrial plants or canneries, it should not be used in concrete unless tests indicate that it is satisfactory. Water from such sources should be avoided since the quality of the water could change due to low water or by intermittent tap water is used for casting.

3.2.5 Supplementary Cement Materials

3.2.5.1. Fly Ash

Class F Fly ash obtained from "Bathinda Thermal Power Station, Bathinda", Punjab was used.

3.2.5.2. Silica Fume

Densified silica fume obtained from Mehtab Pvt. Limited

3.2.6 Admixture

Conplast SP430 complies with IS: 9103:1979 and BS: 5075 Part 3 and ASTM-C-494 Type 'F' as a high range water reducing admixture.

Conplast SP430 is based on Sulphonated Napthalene Polymers and is supplied as brown liquid instantly dispersible in water and specially formulated to give high water reduction up to 25%without loss of workability, Specific gravity 1.22 to 1.225 at 30 °C.

3.3. MIXTURE PROPORTIONING

Table 3.7: Mix proportions of SCC

Mixture ID	Cement (kg/m^3)	FA (kg/m^3)	SF (Kg/m^3)	FA (%)	SF (%)	Sand (kg/m^3)	C.A (kg/m^3)	Water ($kg.m^3$)	w/p	SP (kg/m^3)	SP (%)
CM	550	-	-	-	-	910	590	252	0.45	9.0	1.64
SCC1	465	85	-	15	-	910	590	228	0.41	10.73	1.95
SCC2	415	135	-	25	-	910	590	233.3	0.42	9.91	1.80
SCC3	355	195	-	35	-	910	590	242	0.44	9.91	1.80
SCC A	528	-	22	-	4	910	590	228	0.48	9.91	1.80
SCC B	506	-	44	-	8	910	590	240	0.48	9.91	1.80
SCC C	484	-	66	-	12	910	590	246	0.50	9.91	1.80

Where, CM = Control Mix, w/p= Water/ Powder(cement+SCM)

SCC1 = Self-compacting Concrete with 15 % FA as cement replacement.

SCC2 = Self-compacting Concrete with 25 % FA as cement replacement.

SCC3 = Self-compacting Concrete with 35 % FA as cement replacement.

SCC A = Self-compacting Concrete with 4% SF as cement replacement.

SCC B = Self-compacting Concrete with 8% SF as cement replacement.

SCC C = Self-compacting Concrete with 12% SF as cement replacement.

FA = Fly ash,

SF = Silica fume,

CA = Coarse aggregates,

SP = Super plasticizer.

3.4 TESTS CONDUCTED

3.4.1. FRESH CONCRETE TESTS.

SCC differs from conventional concrete in that its fresh properties are vital in determining whether or not it can be placed satisfactorily. The various aspects of workability which control its Filling ability, its Passing ability and its Segregation resistance all need to be carefully controlled to ensure that its ability to be placed remains accepTable (EFNARC, 2000).

A concrete mix can only be classified as Self-compacting Concrete if the requirements for all three characteristics are fulfilled.

- Filling Ability: Ability of to fill a formwork completely under its own weight.
- Passing Ability: Ability to overcome obstacles under its own weight without hindrance. Obstacles are e.g. reinforcement and small openings etc.
- Segregation Resistance: Homogeneous composition of concrete during and after the process of transport and placing.

It is important to appreciate that none of the test methods for SCC has yet been standardised, and the tests described are not yet perfected or definitive. The methods presented here are descriptions rather than fully detailed procedures. They are mainly ad-hoc methods, which have been devised specifically for SCC.

3.4.1.1. U- Box Test Method

Introduction

The test was developed by the Technology Research Centre of the Taisei Corporation in Japan. Sometimes the apparatus is called a "box-shaped" test. The test is used to measure the filling ability of self-compacting concrete. The apparatus consists of a vessel that is divided by a middle wall into two compartments, shown by R1 and R2 in Fig 3.1.

An opening with a sliding gate is fitted between the two sections. Reinforcing bars with nominal diameters of 13 mm are installed at the gate with centre-to-centre spacing of 50 mm. This creates a clear spacing of 35 mm between the bars. The left hand section is filled with about 20 litre of concrete then the gate lifted and concrete flows *upwards* into the other section. The height of the concrete in both sections is measured.

Assessment of test

This is a simple test to conduct, but the equipment may be difficult to construct. It provides a good direct assessment of filling ability, this is literally what the concrete has to do, modified by an unmeasured requirement for passing ability. The 35mm gap between the sections of reinforcement may be considered too close. The question remains open of what filling height *less than* 30 cm. is still acceptable.

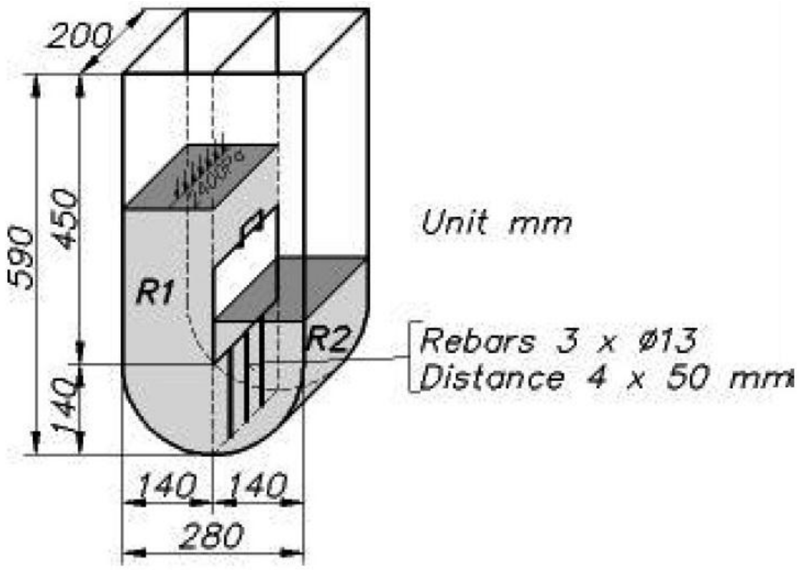

Fig 3.1: U box.

Equipment

- U box of a stiff non absorbing material see Fig 3.1.
- Trowel
- Scoop
- Stopwatch

Procedure

About 20 litre of concrete is needed to perform the test, sampled normally.

Set the apparatus level on firm ground, ensure that the sliding gate can open freely and then close it.

Moisten the inside surfaces of the apparatus, remove any surplus water.

Fill the one compartment of the apparatus with the concrete sample.

Leave it to stand for 1 minute.

Lift the sliding gate and allow the concrete to flow out into the other compartment.

After the concrete has come to rest, measure the height of the concrete in the compartment that has been filled, in two places and calculate the mean (H1). Measure also the height in the other compartment (H2)

Calculate H1 - H2, the filling height.

The whole test has to be performed within 5 minutes.

Interpretation of result

If the concrete flows as freely as water, at rest it will be horizontal, so H1 - H2 = 0. Therefore the nearer this test value, the 'filling height', is to zero, the better the flow and passing ability of the concrete.

3.4.1.2. L- Box Test Method

Introduction

This test is based on a Japanese design for underwater concrete. The test assesses the flow of the concrete, and also the extent to which it is subject to blocking by reinforcement. The apparatus is shown in Fig 3.2

The apparatus consists of a rectangular-section box in the shape of an 'L', with a vertical and horizontal section, separated by a moveable gate, in front of which vertical lengths of reinforcement bar are fitted. The vertical section is filled with concrete, and then the gate lifted to let the concrete flow into the horizontal section. When the flow has stopped, the height of the concrete at the end of the horizontal section is expressed as a proportion of that remaining in the vertical section (H2/H1in the diagram). It indicates the *slope* of the concrete when at rest. This is an indication passing ability, or the degree to which the passage of concrete through the bars is restricted. The horizontal section of the box can be marked at 200mm and 400mm from the gate and the times taken to reach these points measured. These are known as the T20 and T40 times and are an indication for the filling ability.
The sections of bar can be of different diameters and spaced at different intervals: in accordance with normal reinforcement considerations, 3x the maximum aggregate size might be appropriate. The bars can principally be set at any spacing to impose a more or less severe test of the passing ability of the concrete.

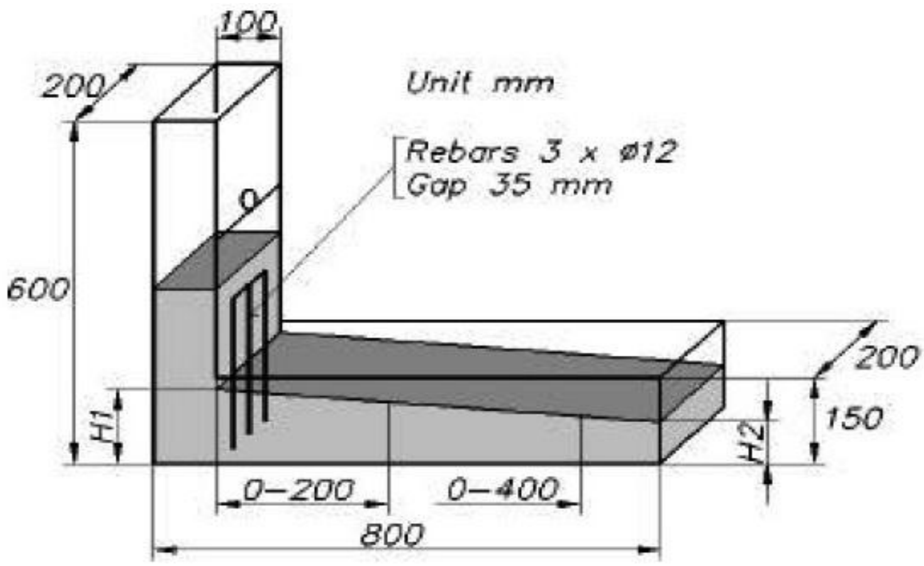

Fig 3.2: L box.

Assessment of test

This is a widely used test, suitable for laboratory, and perhaps site use. It assesses filling and passing ability of SCC, and serious lack of stability (segregation) can be detected visually. Segregation may also be detected by subsequently sawing and inspecting sections of the concrete in the horizontal section. Unfortunately there is no agreement on materials, dimensions, or reinforcing bar arrangement, so it is difficult to compare test results. There is no evidence of what effect the wall of the apparatus and the consequent ‘wall effect’ might have on the concrete flow, but this arrangement does, to some extent, replicate what happens to concrete on site when it is confined within formwork.

Two operators are required if times are measured, and a degree of operator error is inevitable.

Equipment

- L box of a stiff non absorbing material see Fig 3.2
- Trowel
- Scoop
- Stopwatch

Procedure

About 14 litre of concrete is needed to perform the test, sampled normally.

Set the apparatus level on firm ground, ensure that the sliding gate can open freely and then close it.

Moisten the inside surfaces of the apparatus, remove any surplus water.

Fill the vertical section of the apparatus with the concrete sample.

Leave it to stand for 1 minute.

Lift the sliding gate and allow the concrete to flow out into the horizontal section.

Simultaneously, start the stopwatch and record the times taken for the concrete to reach the 200 and 400 mm marks.

When the concrete stops flowing, the distances “H1” and “H2” are measured.

Calculate H2/H1, the blocking ratio.

The whole test has to be performed within 5 minutes.

Interpretation of result

If the concrete flows as freely as water, at rest it will be horizontal, so H2/H1 = 1. Therefore the nearer this test value, the 'blocking ratio', is to unity, the better the flow of the concrete. The EU research team suggested a minimum acceptable value of 0.8. T20 and T40 times can give some indication of ease of flow, but no suitable values have been generally agreed. Obvious blocking of coarse aggregate behind the reinforcing bars can be detected visually.

3.4.1.3. V-Funnel Test Method

Introduction

The test was developed in Japan and used by Ozawa (2001). The equipment consists of a V-shaped funnel, shown in Fig 3.3. An alternative type of V-funnel, the O funnel, with a circular section is also used in Japan. The described V-funnel test is used to determine the filling ability (flowability) of the concrete with a maximum aggregate size of 20mm. The funnel is filled with about 12 litres of concrete and the time taken for it to flow through the apparatus measured. After this the funnel can be refilled concrete and left for 5 minutes to settle. If the concrete shows segregation then the flow time will increase significantly.

Assessment of test

Though the test is designed to measure flowability, the result is affected by concrete properties other than flow. The inverted cone shape will cause any liability of the concrete to block to be reflected in the result – if, for example, there is too much coarse aggregate. High flow time can also be associated with low deformability due to a high paste viscosity, and with high inter-particle friction. While the apparatus is simple, the effect of the angle of the funnel and the wall effect on the flow of concrete are not clear.

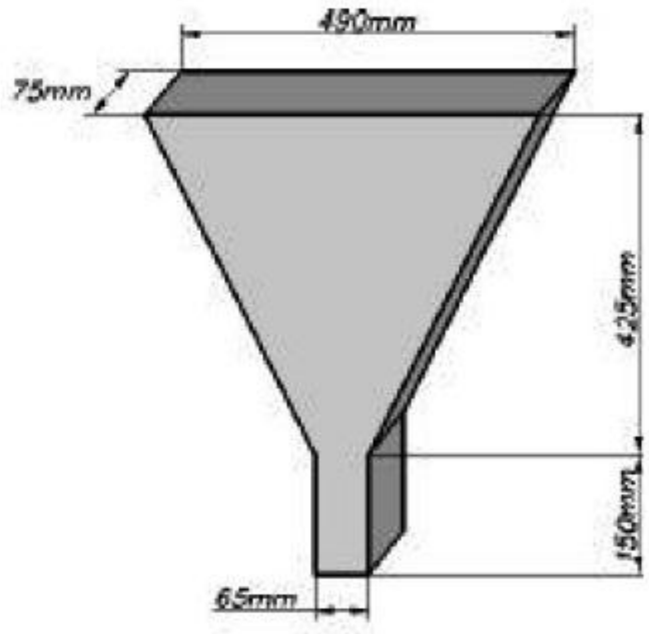

Fig 3.3: V- Funnel equipment.

Equipment

- V-funnel
- Bucket (±12 litre)
- Trowel
- Scoop
- Stopwatch

Procedure for flow time

About 12 litre of concrete is needed to perform the test, sampled normally.

Set the V-funnel on firm ground.

Moisten the inside surfaces of the funnel.

Keep the trap door open to allow any surplus water to drain.

Close the trap door and place a bucket underneath.

Fill the apparatus completely with concrete without compacting or tamping, simply strike off the concrete level with the top with the trowel.

Open within 10 sec after filling the trap door and allow the concrete to flow out under gravity.

Start the stopwatch when the trap door is opened, and record the time for the discharge to complete (the flow time). This is taken to be when light is seen from above through the funnel.

The whole test has to be performed within 5 minutes.

Interpretation of result

This test measures the ease of flow of the concrete; shorter flow times indicate greater flowability. For SCC a flow time of 10 seconds is considered appropriate. The inverted cone shape restricts flow, and prolonged flow times may give some indication of the susceptibility of the mix to blocking. After 5 minutes of settling, segregation of concrete will show a less continuous flow with an increase in flow time.

3.4.1.4. Slump flow test

Introduction

The slump flow is used to assess the horizontal free flow of SCC in the absence of obstructions. It was first developed in Japan for use in assessment of underwater concrete. The test method is based on the test method for determining the slump. The diameter of the concrete circle is a measure for the filling ability of the concrete.

Assessment of test

This is a simple, rapid test procedure, though two people are needed if the T_{50} time is to be measured. It can be used on site, though the size of the base plate is somewhat unwieldy and level ground is essential. It is the most commonly used test, and gives a good assessment of filling ability. 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. It can be argued that the completely free flow, unrestrained by any boundaries, is not representative of what happens in practice in concrete construction, but the test can be profitably be used to assess the consistency of supply of ready-mixed concrete to a site from load to load.

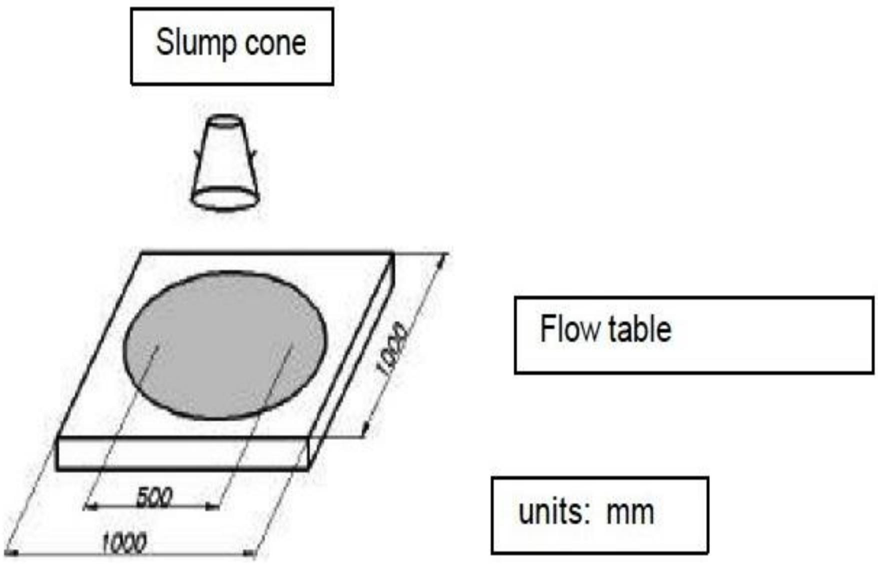

Fig 3.4: Slump flow test equipment.

Equipment

The apparatus is shown in Fig 3.4

- Mould in the shape of a truncated cone with the internal dimensions 200 mm diameter at the base, 100 mm diameter at the top and a height of 300 mm, conforming to EN 12350-2
- Base plate of a stiff non absorbing material, at least 700mm square, marked with a circle marking the central location for the slump cone, and a further concentric circle of 500mm diameter
- Trowel

- Scoop
- Ruler
- Stopwatch (optional)

Procedure

About 6 litre of concrete is needed to perform the test, sampled normally.

Moisten the base plate and inside of slump cone, Place base plate on level stable ground and the slump cone centrally on the base plate and hold down firmly.

Fill the cone with the scoop. Do not tamp, simply strike off the concrete level with the top of the cone with the trowel.

Remove any surplus concrete from around the base of the cone.

Raise the cone vertically and allow the concrete to flow out freely.

Simultaneously, start the stopwatch and record the time taken for the concrete to reach the 500mm spread circle. (This is the T50 time).

Measure the final diameter of the concrete in two perpendicular directions.

Calculate the average of the two measured diameters. (This is the slump flow in mm).
Note any border of mortar or cement paste without coarse aggregate at the edge of the pool of concrete.

Interpretation of result

The higher the slump flow (SF) value, the greater its ability to fill formwork under its own weight. A value of *at least* 650mm is required for SCC. There is no generally accepted advice on what are reasonable tolerances about a specified value, though ± 50mm, as with the related flow Table test, might be appropriate. The T50 time is a secondary indication of flow.

A lower time indicates greater flowability. The Brite EuRam research suggested that a time of 3-7 seconds is acceptable for civil engineering applications, and 2-5 seconds for housing applications. In case of severe segregation most coarse aggregate will remain in the centre of the pool of concrete and mortar and cement paste at the concrete periphery. In case of minor segregation a border of mortar without coarse aggregate can occur at the edge of the pool of concrete. If none of these phenomena appear it is no assurance that segregation will not occur since this is a time related aspect that can occur after a longer period.

3.4.2. HARDENED CONCRETE TESTS.

3.4.2.1. Compressive strength (IS: 516-1959)

Objective: Determination of compressive strength of concrete.

Apparatus: Testing Machine: The testing machine may be of any reliable type of sufficient capacity for the tests and capable of applying the load at the specified rate. The permissible error shall not be greater than 2 percent of the maximum load. The testing machine shall be equipped with two steel bearing platens with hardened faces. One of the platens shall be fitted with a ball seating in the form the portion of the sphere, the centre of which coincides with the central point of the face of the platen. The other compression platen shall be plain rigid bearing block. The bearing faces of both platens shall be at least as larger as , and preferably larger than the normal size of the specimen to which the load is applied. The bearing surface of the platens, when new, shall not depart from a plane by more than 0.01mm at any point, and they shall be maintained with a permissible variation limit of 0.02mm, the movable portion of the spherical seated compression platen shall be held on the spherical seat, but the design shall be such that the bearing face can be rotated freely and tilted through small angles in any direction.

Age at test: Tests shall be made at recognised ages of the test specimens, the most usual being 7 and 28 days. The ages shall be calculated from the time of the addition of water of the dry ingredients.

Number of Specimens: At least three specimens, preferably from different batches, shall be made for testing at each selected age.

Procedure: Specimens stored in water shall be tested immediately on removal from the water and while they are still in the wet condition. Surface water and grit shall be wiped off the specimens and any projecting find removed specimens when received dry shall be kept in water for 24 hours before they are taken for testing. The dimensions of the specimens to the nearest 0.2mm and their weight shall be noted before testing. Placing the specimen in the testing machine the bearing surface of the testing machine shall be wiped clean and any loose sand or other material removed from the surface of the specimen, which are to be in contact with the compression platens. In the case of cubes, the specimen shall be placed in the machine in such a manner that the load shall be applied to opposite sides of the cubes as cast, that is, not to the top and bottom. The axis of the specimen shall be carefully aligned with the centre of thrust of the spherically seated platen. No packing shall be used between the faces of the test specimen and steel platen of the testing machine. As the spherically seated block is brought to bear on the specimen, the movable portion shall be rotated gently by hand so that uniform seating may be obtained. The load shall be applied without shock and increased continuously at a rate of approximately 140 Kg/cm^2/min. until the resistance of the specimen to the increasing load breaks down and any unusual features in the type of failure shall be noted.

Calculation: the measured compressive strength of the specimen shall be calculated by dividing the maximum load applied to the specimen during the test by the cross sectional area, calculated from the mean dimensions of the section and shall be expressed to the nearest Kg/cm^2. Average of three values shall be taken as the representative of the batch provided the individual variation is not more than +/-15 percent of the average. Otherwise repeat tests shall be made. A correction factor according to the height/diameter ratio of specimen after capping shall be obtained from the curve shown in Fig.1 of IS: 516-1959. The product of this correction factor and the measured compressive strength shall be known as the corrected compressive strength this being the equivalent strength of a cylinder having a height/diameter ratio of two. The equivaqlent cube strength of the concrete shall be determined by multiplying the corrected cylinder by 5/4.

3.4.2.2. Sorptivity

Sorptivity coefficient can be determined by means of simple test allowing one face of concrete specimen is in contact with water and the mass (non-destructive) or height (destructive) of water absorbed by capillary suction is measured at predefined intervals. For this, Cubical specimens of size 150 mm were casted and cured for 28 days. After curing period cubes were kept in natural air to get dry for 4 hours. Then 4 sides of concrete specimen were sealed by electrician tape to avoid evaporative effect as well to maintain uniaxial water flow during the test and opposite faces were left open. One face of the specimen was in contact with water whilst the water absorption at predefined intervals. The test started with the registration of samples weight and, afterwards, they were placed in a recipient in contact with a height of water capable to submerge them about 5mm. After a predefined period of time, the samples were removed from the recipient to proceed to weight registration. Before the weight, the samples superficial water was removed with a wet cloth. Immediately after the weight, the samples were replaced in the recipient till reach the following time. The procedure was repeated, consecutively, until the last reading.

The Sorptivity coefficient can be calculated by the following expressions.

$$S = (Q/A) / \sqrt{T}$$

Where S is the Sorptivity (cm/min$^{1/2}$), Q is the mass of water absorbed in kg, A is the surface area in contact with water in cm^2 and t is the time in minutes (Bentz et.al. 2001).

3.4.2.3. Sulphate Resistance

For this purpose, cylindrical specimens of size 150 mm diameter × 300 mm height were cast. The test was conducted at the end of 28 days of curing. The specimens were then subjected to a solution with sodium sulphate; the specimens were placed in a solution of 18 g/l of sodium sulphate in distilled water. A propeller was placed in the basin in order to secure a good circulation of the solution around the specimens. The method for investigation of the damage has been measurement of surface scaling of material by weighing at the age of 3, 7, 14, 21 days (Persson, 2003)

3.4.2.4. Shrinkage

When the concrete dries after curing under wet conditions, it shrinks during the drying process. This is called shrinkage. This test is as per IS: 1489.

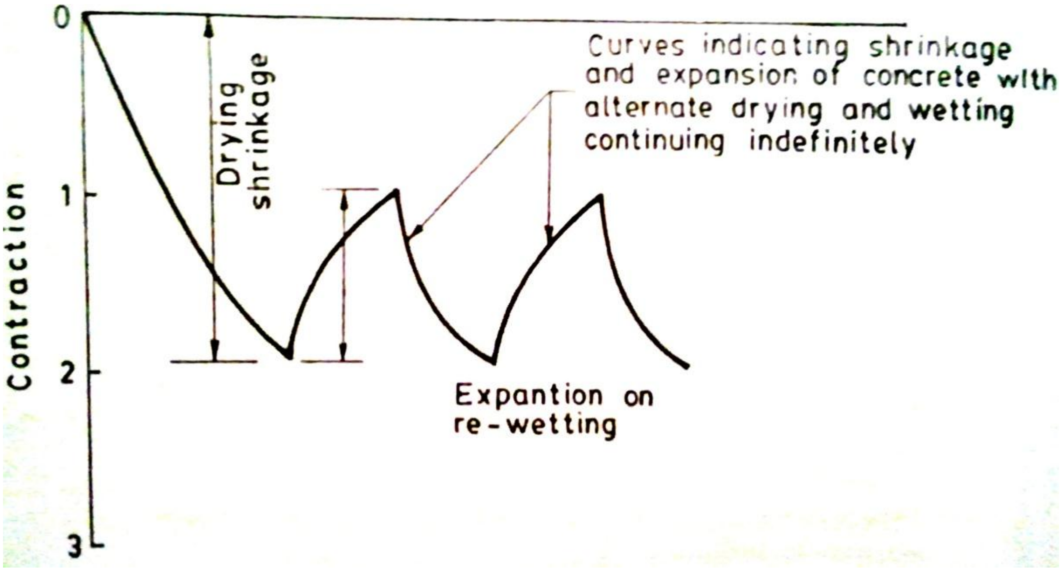

Fig 3.5: Drying Shrinkage.

For the casting, Shrinkage Bar mould is used as per AIM-402 to AIM 407. Size of the specimen is 25 x 25 x 250 mm.

During casting stainless steel plugs were mounted with spherical ends into the specimens and cured for 28 days.

The initial lengths (L_1) in mm of the wet specimen measured on the shrinkage tester just after the removal from the curing tank. The reference points were fixed at the end of specimens for taking the measurements and then specimens were placed in the oven at the temperature of 50ºC for a week. After one weak the specimens were allowed to cool for four hours and then again the length (L_2) was measured with shrinkage tester. Again for one week the specimens were immersed in water tank, then after one week length (L_3) in mm was measured.

Then shrinkage can be measured with the formula as under:

$$[\text{Dry Measurement } (L_2) - \text{Wet measurement } (L_3)] / \text{Dry measurement } (L_2)$$

Expressed in percentage, and shrinkage is measured at the age of 5, 10, 15, 20 days (after the 28 days initial curing.

3.4.2.5. Water Absorption

Cubical specimens of size 75 mm were cast for conducting water absorption tests, by completely immersing dried cube specimens in water at 25ºC for 96 hours and noting the amount of water absorbed per unit initial mass in percentage after the age of 28 days and 56 days. This gives percentage water absorbed.

CHAPTER4: RESULTS AND DISCUSSIONS

4.1. GENERAL

In this chapter the parameters studied on the control and concrete made with replacement of fly ash and silica fume with cement in self-compacting concrete are discussed. The parameters such as Compressive strength, Water absorption, Sorptivity, Sulphate resistance are discussed and comparisons between the various mixes are represented.

4.2. FLY ASH

4.2.1. Fresh Concrete Properties

In order to study the effect on fresh concrete properties when fly ash is added into the concrete as cement replacement, the SCC containing different proportion of fly ash were tested for Slump flow, V-funnel, U-Box, L-box.

The results of fresh properties of all Self-compacting fly ash concretes are included in Table 4.1. The Table shows the properties such as slump flow, V-funnel flow times, L-box, U- box. In terms of slump flow, all SCCs exhibited satisfactory slump flows in the range of 550–800 mm, which is an indication of a good deformability.

Table: 4.1 Fresh concrete properties (Fly Ash)

Mixture ID	Slump (mm)	V-funnel (seconds)	L-Box (H2/H1)	U-box(H1-H2)
SCC1(15% FA)	687	9	0.9	30
SCC1(15% FA)	590	13	-	-
SCC2(25% FA)	704	11	-	35
SCC2(25% FA)	740	12	0.9	35
SCC2(25% FA)	720	9	1.0	-

SCC3(35% FA)	630	-	-	40
SCC3(35% FA)	680	13	-	-
SCC3(35% FA)	640	11	0.8	30

As per EFNARC, time ranging from 6 to 12 seconds is considered adequate for a SCC. The V-funnel flow times were in the range of 4–10 seconds. Test results of this investigation indicated that all SCC mixes meet the requirements of allowable flow time. Maximum size of coarse aggregate was kept as 16 mm in order to avoid blocking effect in the L-box. The gap between re-bars in L-box test was 35 mm. The L-box ratio H2/H1 for the mixes was above 0.8 which is as per EFNARC standards. U-box difference in height of concrete in two compartments was in the range of 5–40 mm. All the Fresh properties of concrete values were in good agreement to that of the values given by European guidelines.

Fig. 4.1: Slump flow test.

Fig. 4.2: L-Box test.

4.2.2. Compressive Strength

In order to study the effect on compressive strength when fly ash is added into self-compacting concrete as cement replacement, the cube containing different proportion of fly ash were prepared and kept for curing for 7, 28 and 56 days. The test was conducted on ASTM of capacity 3000 KN. From the results (Table 4.2) it is concluded that the 56 days strength of all the mixes is invariably higher than corresponding 7 days and 28 days strength, this is due to continuous hydration of cement with concrete.

Table 4.2: Compressive strength of SCC mixes.

MIX	Compressive Strength (N/mm^2)			Average Compressive Strength(N/mm^2)		
	7 days	28days	56 days	7 days	28 days	56 days
SCC1 (15% FA)	19	27.5	36.5	18.9	27.7	38.1
	18.4	26.9	38.7			
	19.3	28.7	39.2			
SCC2 (25% FA)	16.1	24.7	33.7	17.1	24.3	32.5
	16.7	23.6	31.4			
	18.5	24.6	32.4			
SCC3 (35% FA)	15.6	22.7	29.7	14.6	22.3	29.1
	14.6	22.9	30.0			
	13.5	21.2	27.8			
CM	20.2	28.4	36.1	20.6	28.9	33.0
	23.5	29.5	31.0			
	18	28.7	32.1			

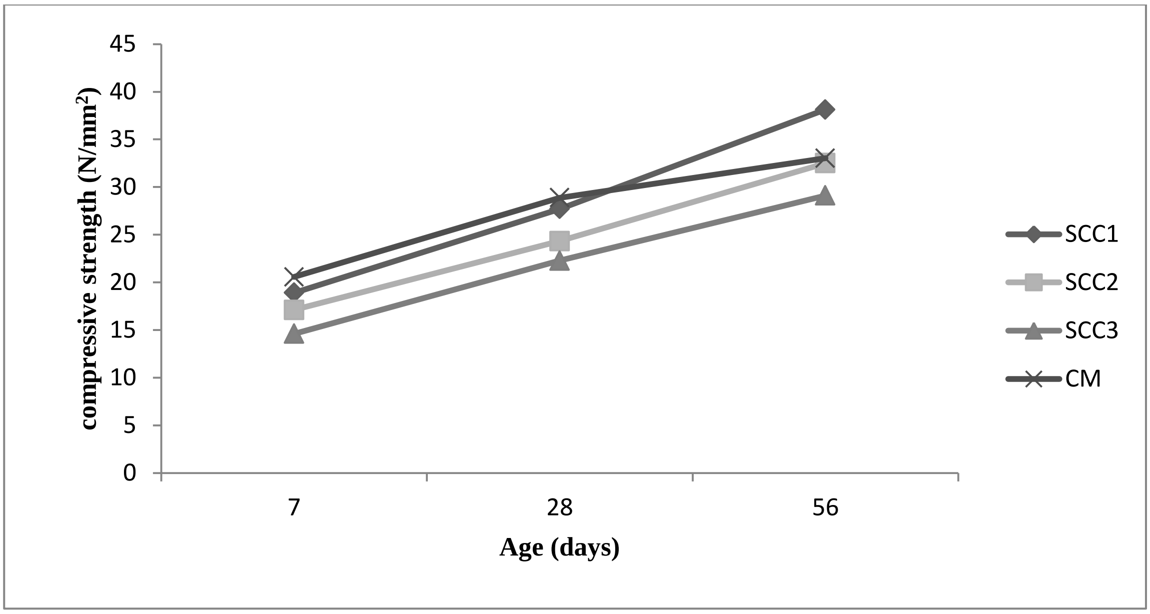

Fig.4.3. Compressive strength of SCC mixes at various ages.

Effect of percentage of Fly ash on compressive strength of self-compacting concrete

The compressive strength tests results of SCC mixes are given in Table 4.2 and shown in Fig. 4.3. With the increase in fly ash content from 15–35%, SCC mixes developed compressive strengths between 18.9 and 13.9 MPa at 7 days; between 27.7 and 20.8 at 28 days; between 38.13 and 26.63 at 56 days. The compressive strength increased with a decrease in the percentage of the fly ash and the water-to-cementitious materials ratio. An increase of about 24% strength at 28 days and 30% at 56 days was observed with the decrease of fly ash content from 35% (SCC3) to 15% (SCC1). The strength values at 7 days of SCC5 (35% fly ash) are comparable with the results reported by Siddique (2010).

As reported by Xie et al. (2000) the strength values at 28 days age of curing. SCC4 (30% fly ash) attained strength of 23.98 MPa, 30.66 MPa, at 7 and 28, days, respectively. Similarly, SCC3 (25% fly ash) attained strength corresponding to 25.52 MPa, 31.47 MPa, at 7 and 28 days, respectively.

4.2.3. Water Absorption

In order to study the water absorption when fly ash is added into self-compacting concrete as cement replacement, the cube containing different proportion of fly ash were prepared and kept for initial curing for 28 days. After the initial curing the water absorption was carried out at the age of 28 days and 56 days as per test procedure mentioned in above chapter.

From the results (Table 4.3) it is observed that initially water absorption increases because of the inert behaviour of fly ash and the more pore percentage as compare to control mix at the initial ages, after that when fly ash reaction mechanism takes place there is no significant rise in percentage of water absorbed at 28 days and at 56 days. This is due to continuous hydration of cement with concrete, and also when the fly ash is incorporated in concrete, the calcium hydroxide liberated during hydration of cement reacts with the amorphous aluminosilicates (the pozzolanic compound present in fly ash) and produce a binding gel which fills the pores in concrete.

The Fig. 4.4 shows that concrete (SCC3) shows higher absorption i.e. 2.67 % at the age of 28 days and 3.59 % at the age of 56 days than that of concrete (SCC1) i.e. 0.46 % at the age of 28 days and 0.67 % at the age of 56 days, that means water absorption values of all the Self-compacting fly ash concretes were slightly higher than the control mix. The absorption increased with an increase in percentage of fly ash replacement. The results are comparable with the results reported by Dinakar et al., (2008), he indicated the highest absorption of 8.84 % than any other concrete, this was due to very high replacement of cement with fly ash i.e. nearly 80 %.

Table 4.3: percentage of water absorbed at various ages

Mix	Percentage of Water absorbed in 28 days	Percentage of Water absorbed in 56 days
SCC1 (15% FA)	0.406	0.677
SCC2 (25% FA)	0.663	1.194
SCC3 (35% FA)	2.670	3.592
CM	0.206	0.396

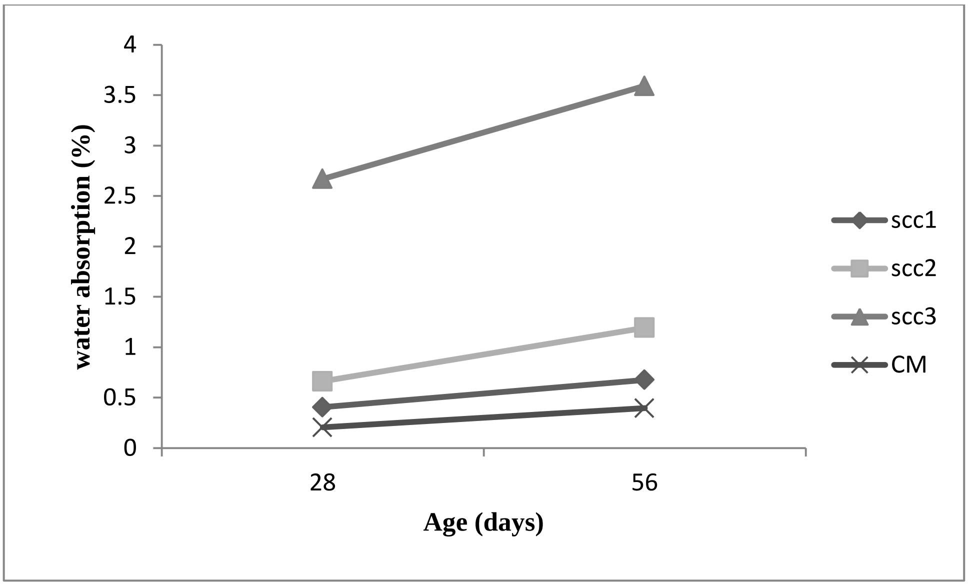

Fig.4.4: Percentage of water absorbed of SCC mixes at various ages.

Absorption is mainly influenced by the paste phase primarily; it is dependent on the extent of interconnected capillary porosity in the paste. Concrete mixes with higher paste contents are bound to have higher absorption values than concretes with lower paste content (at consistent w/c). The lower water absorption thus observed for control mix is attributed to the relatively lower paste volume i.e., smaller capillary pore volume.

4.2.4. Shrinkage

When the concrete dries after curing under wet conditions, it shrinks during the drying process, this is called Shrinkage. The change in length was measured as per the guidelines discussed in the previous chapter.

From the results it is obtained that increasing the amount of fly ash results in a systematic reduction in shrinkage. At low FA content i.e. 15 % (SCC1) the shrinkage is nearly same as Control Mix, but there is noticeable change in high FA content 35 % (SCC3) and in Control Mix i.e. -0.030 to -0.058 cm in 5 days, -0.042 to -0.086 cm in 10 days, -0.060 to -0.113 cm in 15 days and -0.069 to -0.132 cm in 20 days, as shown in Table 4.4 and Fig. 4.5.

The final (20 days) shrinkage is approximately 2 times less than the control mix.

This happens because amount of fly ash gets hydrated with the age and fills the vacant pores, hence increase the shrinkage resistance of concrete.

Table 4.4: Shrinkage value at various ages

	Shrinkage value (cm)			
Mix	**5 days**	**10 days**	**15 days**	**20 days**
SCC1 (15% FA)	-0.054	-0.076	-0.097	-0.120
SCC2 (25% FA)	-0.032	-0.062	-0.078	-0.092
SCC3 (35% FA)	-0.030	-0.042	-0.060	-0.069
CM	-0.058	-0.086	-0.113	-0.132

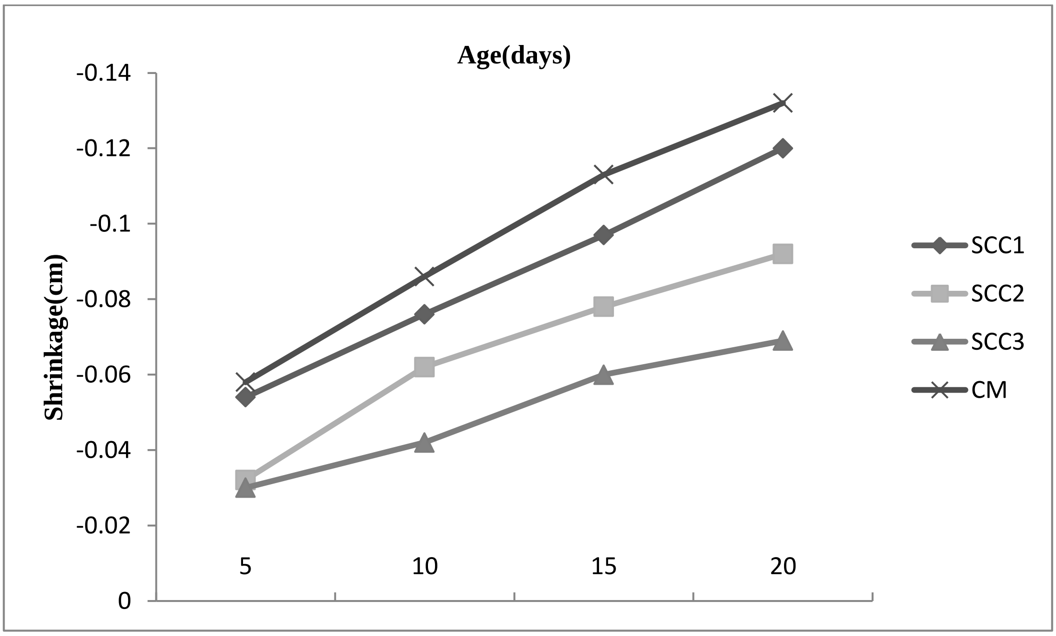

Fig.4.5: Shrinkage value at various ages.

Fig.4.6: Shrinkage bar mould.

Fig. 4.7: Concrete Moulding.

Fig. 4.8: Specimens for Shrinkage.

Fig. 4.9: Specimens for Shrinkage.

Fig. 4.10: Length measurement with Shrinkage tester.

Khatib (2008) has shown the same results as per this study. He has also shown that increased amount of FA improves the shrinkage capacity. The shrinkage values obtained for SCC are higher than those obtained for control mix. He has shown that at high FA content (60%) the 56 days shrinkage is reduced to half and with very high FA content (80%) the shrinkage is about one third compared with that of the control.

Safiuddin et al. (2008) has shown that the reduced coarse aggregate content and increased amount of cementing material are expected to cause more shrinkage in SCC. But the porosity also affects the drying shrinkage of concrete. As the porosity is reduced in SCC, it compensates the negative effects of aggregate and binder on shrinkage. In addition, the shrinkage tends to decrease in SCC since a very small amount of free water is available in the system. Also, SCC has minimum empty voids on concrete surface that are largely responsible for shrinkage.

4.2.5. Sorptivity

Sorptivity coefficient was determined by means of simple test allowing one face of concrete specimen in contact with water and the mass of water absorbed by capillary suction was measured at predefined intervals. For this, cubical specimens of size 150 mm were casted and cured for 28 days. After curing period cubes were kept in natural air to get dry for 4 hours. Then 4 sides of concrete specimen were sealed by a water proof seal preferably called as Elastyseal (a product of Araldiet) in the market. To avoid evaporative effect as well to maintain uniaxial water flow during the test and opposite faces were left open. After a predefined period of time, the samples were removed from the recipient to proceed to weight registration. Before the weight, the sample's superficial water was removed with a wet cloth. Immediately after the weight, the samples were replaced in solution till reach the following time. The procedure was repeated, consecutively, until the last reading. The weight noted is shown in Table 4.5

Table 4.5: Evolution of water absorption by capillarity carried out with ages

	Water absorbed by capillarity (kg/cm^2)					
Mix	**15 min**	**30 min**	**1 hour**	**24 hours**	**48 hours**	**72 hours**
SCC1 (15% FA)	0.00008	0.00014	0.0002	0.00031	0.00041	0.00051
SCC2 (25% FA)	0.00006	0.00011	0.00018	0.00022	0.00031	0.00036
SCC3 (35% FA)	0.00005	0.00009	0.00016	0.00018	0.00021	0.00033
CM	0.0001	0.0002	0.00025	0.00037	0.00047	0.00057

From the results it is obtained that increasing the amount of fly ash results in a systematic reduction in Sorptivity. At low FA content i.e. 15 % (SCC1) the water absorbed by capillary action is nearly same as control mix, but there is a noticeable difference in the capacity of SCC3 (35%) and control mix, the control mix has approximately 70 % high sorption capacity than SCC3 (35%). However by using high amount of FA the Sorptivity decreases as shown in Table 4.5 and Fig. 4.11.

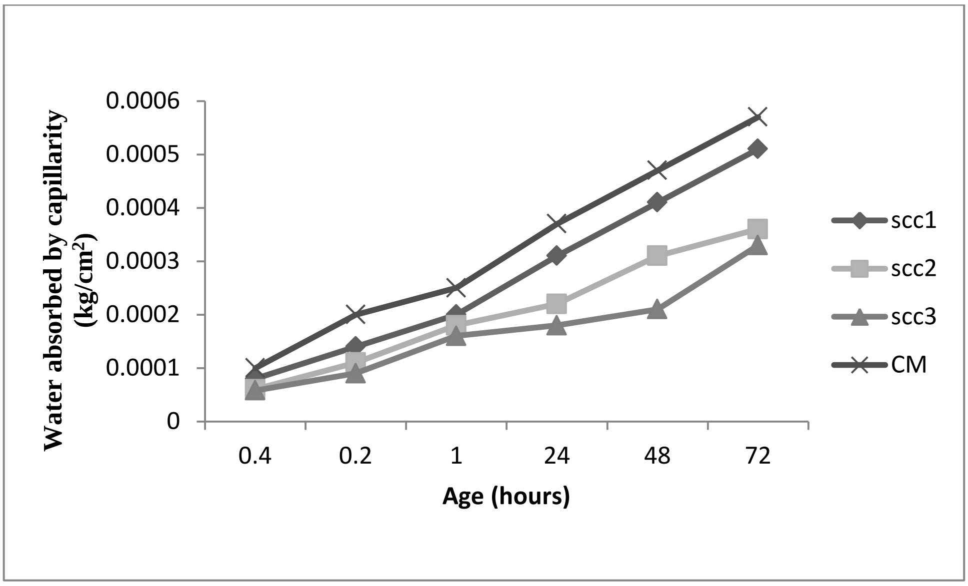

Fig.4.11: Evolution of Sorptivity carried out with ages.

Fig.4.12: Specimen Sealed with water seal.

Fig. 4.13: Water seal used.

Fig. 4.14: Specimen immersed in water at a height of 5 mm.

In the same manner Pereira-de-oliveira et al. (2005) and Turk et al. (2007) also observed that with the increase in FA content the Sorptivity decreases and a concrete without cementitious materials always possess high Sorptivity value.

4.2.6. Sulphate Resistance

External sulfate attack (ESA) to cementitious matrix is a complex process that involves the movement of sulfate ions through the pores by means of different mechanisms of transportation and the interaction of aggressive solution with some compounds of cement paste (AFm phases, hydrogarnet phases, unhydrated alumina phases and CH) to form expansive compounds (ettringite and gypsum) that produce cracking, strength loss and softening. The most important factor to prevent external sulfate attack is to reduce the permeability of the concrete (low water/cement ratio, high cement content, well compacted and well cured). Hence usage of supplementary cementing materials increases the resistance against sulphate attack. This makes it clear that using the high amount of FA will increase the sulphate resistance capacity of concrete.In an acidic sulfate environment ($pH<7$), gypsum formation causes local expansion, spalling and strength retrogression. The acid media contribute to the gradual removal of CH from the paste until complete depletion, which promotes decomposition of C–S–H that causes loss of adhesion and stiffness.

After 28 days of curing the test was conducted at 3, 7, 14 and 21 days. The Table 4.6 and Fig. 4.15 shows the percentage loss in weight of concrete specimens made by using various amount of replacements in cement quantity by FA with respect to age.

Table 4.6: Percentage of weight loss with ages

	Percentage loss in weight			
MIX	**3 days**	**7 days**	**14 days**	**21 days**
SCC1 (15% FA)	-2.187	-2.335	-4.610	-6.804
SCC2 (25% FA)	-1.442	-1.620	-3.364	-5.467
SCC3 (35% FA)	-0.600	-0.437	-1.885	-3.913
CM	-2.700	-3.130	-5.200	-7.410

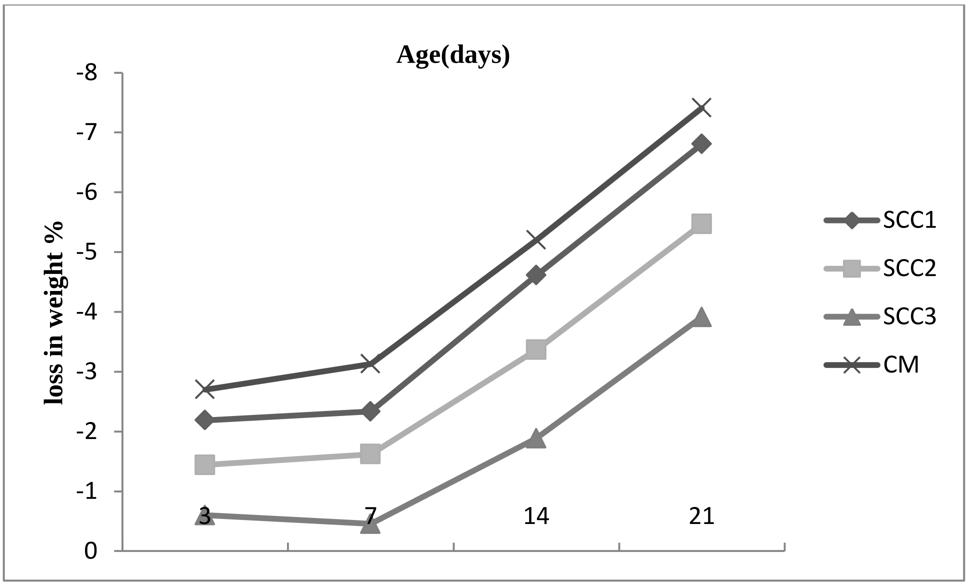

Fig.4.15: Percentage of weight loss with ages.

Fig.4.16: Specimen dipped in Sodium Sulfate solution.

Here as per results obtained there is a remarkable loss in weight of Control Mix, as compare to best concrete out of these i.e. SCC3. At the age of 3 days SCC3 posses 0.600 % loss as compare to CM i.e. 2.700 %, at the age of 7 days SCC3 losses 0.437 % as CM lost 3.130 % and by the last reading that is at the age of 21 days SCC3 lost 3.931 % and CM lost 7.410 % of weight.

Najimi et al. (2011), Safiuddin et al. (2008) and Dinakar et al. (2008) has shown the similar results that increasing the FA content will increase Sulphate Resistance of SCC.

4.3. SILICA FUME

Because of the extreme fineness and very high amorphous silicon dioxide content, silica fume is a very reactive pozzolanic material. As the Portland cement in concrete begins to react chemically, it releases calcium hydroxide. The silica fume reacts with this calcium hydroxide to form additional binder material called calcium silicate hydrate, which is very similar to the calcium silicate hydrate formed from Portland cement. It is an additional binder that gives silica-fume concrete its improved properties.

Mechanism of silica fume in concrete can be studied basically under three roles:

- **Pore-size Refinement and Matrix Densification:** The presence of silica fume in the Portland cement concrete mixes causes considerable reduction in the volume of large pores at all ages. It basically acts as filler due to its fineness and because of which it fits into spaces between grains in the same way that sand fills the spaces between particles of coarse aggregates and cement grains fill the spaces between fine aggregates grains.
- **Reaction with Free-Lime (From Hydration of Cement)** CH crystals in Portland cement pastes are a source of weakness because cracks can easily propagate through or within these crystals without any significant resistance affecting the strength, durability and other properties of concrete. Silica fume which is siliceous and aluminious material reacts with CH resulting reduction in CH content in addition to forming strength contributing cementitious products which in other words can be termed as ‘‘Pozzolanic Reaction’’.
- **Cement Paste–Aggregate Interfacial Refinement** In concrete the characteristics of the transition zone between the aggregate particles and cement paste plays a significant role in the cement-aggregate bond. Silica fume addition influences the thickness of transition phase in mortars and the degree of the orientation of the CH

crystals in it. The thickness compared with mortar containing only ordinary Portland cement decreases and reduction in degree of orientation of CH crystals in transition phase with the addition of silica fume. Hence mechanical properties and durability is improved because of the enhancement in interfacial or bond strength. Mechanism behind is not only connected to chemical formation of C–S–H (i.e. pozzolanic reaction) at interface, but also to the microstructure modification (i.e. CH) orientation, porosity and transition zone thickness) as well.

4.3.1 Fresh Concrete Properties

In order to study the effect on fresh concrete properties when silica fume is added into the concrete as cement replacement, the SCC containing different proportion of silica fume were tested for Slump flow, V-funnel, U-Box, L-box.

The results of fresh properties of all Self-compacting silica fume concretes are included in Table 4.7. The Table shows the properties such as slump flow, V-funnel flow times, L-box, U- box. In terms of slump flow, all SCCs exhibited satisfactory slump flows in the range of 550–800 mm, which is an indication of a good deformability.

Table 4.7: Fresh Concrete Properties (Silica fume)

Mixture ID	**Slump (mm)**	**V-funnel (seconds)**	**L-Box (H2/H1)**	**U-box(H1-H2)**
SCC A (4% SF)	600	11	0.9	34
SCC B (8% SF)	640	13	0.9	40
SCC C (12% SF)	670	9	0.9	35

As per EFNARC, time ranging from 6 to 12 seconds is considered adequate for a SCC. The V-funnel flow times were in the range of 4–10 seconds. Test results of this investigation indicated that all SCC mixes meet the requirements of allowable flow time. Maximum size of coarse aggregate was kept as 16 mm in order to avoid blocking effect in the L-box. The gap between re-bars in L-box test was 35 mm. The L-box ratio H2/H1 for the mixes was above 0.8 which is as per EFNARC standards. U-box difference in height of concrete in two compartments was in the range of 5–40 mm. All the Fresh properties of concrete values were in good agreement to that of the values given by European guidelines.

4.3.2 Compressive Strength

In order to study the effect on compressive strength, when Silica fume is added into self-compacting concrete as cement replacement, the cube containing different proportion of fly ash were prepared and kept for curing for 7, 28 days.

Table 4.8: Compressive strength of SCC mixes with Silica fume

MIX	Compressive Strength (N/mm^2)		Average Compressive Strength (N/mm^2)	
	7 days	28 days	7 days	28 days
SCC A (4% SF)	26.8	37.1	26.9	39.7
	25.7	42.1		
	28.2	39.8		
SCC B (8% SF)	27.7	40.1	29.6	41.4
	30.1	42.3		
	31.0	41.7		
SCC C (12% SF)	25.1	33.4	25.3	37.2
	24.1	37.8		
	26.8	40.3		
CM	20.2	28.4	20.5	28.9
	23.5	29.5		
	18	28.7		

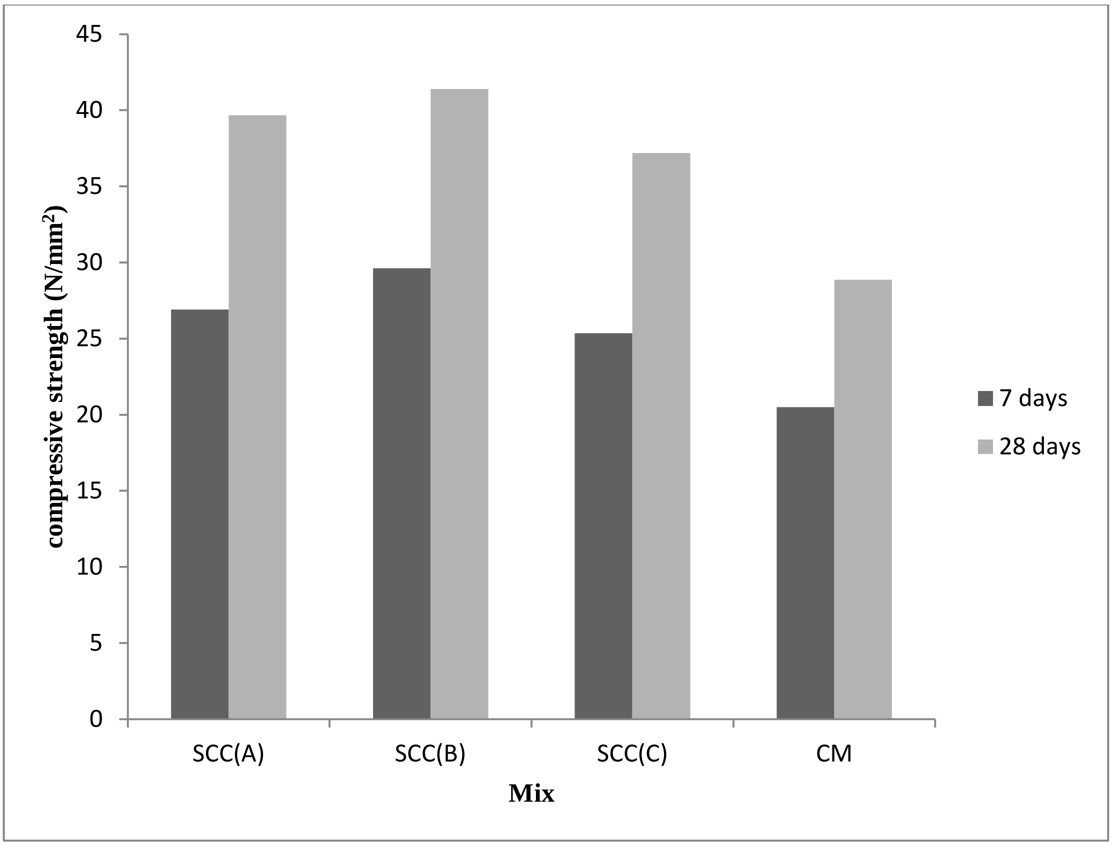

Fig.4.17: Compressive strength of SCC mixes at various ages with Silica fume.

The influence of silica fume on compressive strength of self-compacting concrete is given in Table 4.8 and Fig.4.17. The percentage of silica fume was 4%, 8% and 12% and the water-cement ratios ranged from 0.4 to 0.5. The test results indicated that, 4 to 8 percent by mass replacement of silica fume for cement gives the highest strength for short and long terms and when silica fume is replaced by 12% the strength decreases. Compressive strength of silica fume concrete at 28 days compared to control mix was increased by 37 to 50 percent with silica added 4 to 8% respectively. Khaloo and Houseinian (1999) has reported that the compressive strength of silica fume concrete at 28 days compared to control mix increases by 20 to 40 percent, for all the variables considered.

4.3.3. Water Absorption

In order to study the water absorption when silica fume is added into self-compacting concrete as cement replacement, the cube containing different proportion of Silica fume were prepared and kept for initial curing for 28 days. After the initial curing the water absorption was carried out at the age of 28 days and 56 days as per test procedure mentioned in above chapter.

Table 4.9: Percentage of water absorbed at various ages

Mix	Percentage of Water absorbed in 28 days.	Percentage of Water absorbed in 56 days.
SCC A	0.133	0.230
SCC B	0.113	0.150
SCC C	0.090	0.110
CM	0.206	0.396

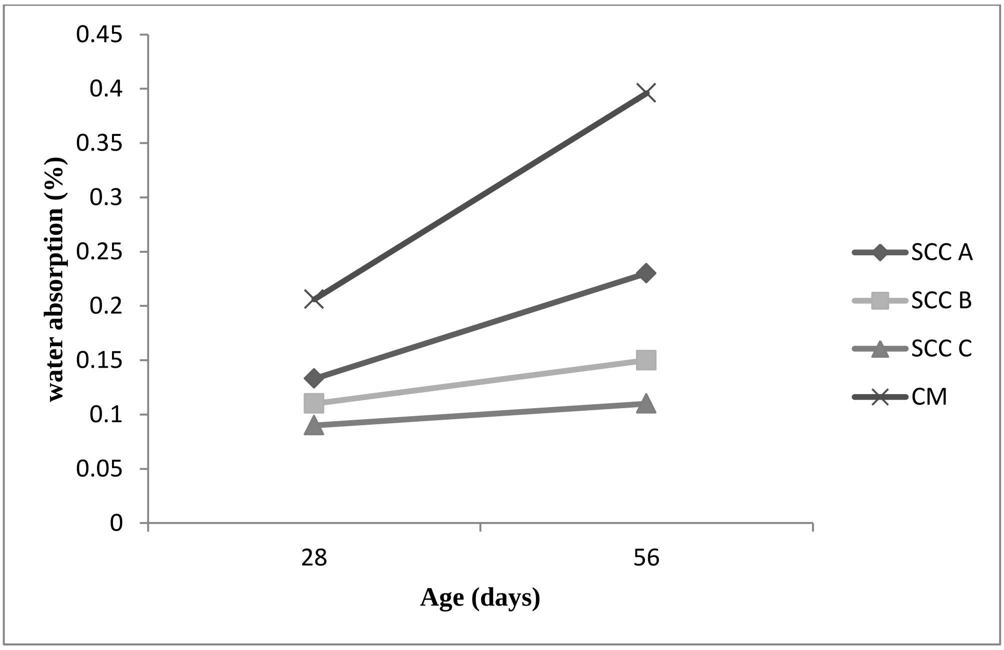

Table 4.18: Percentage of Water absorbed of SCC mixes at various ages

From the results, it is obtained concrete mix without silica Fume (SF) shows high capacity of water absorption whereas concrete with SF shows a very low water absorption this is because of the particle size of SF i.e. mostly spheres with a mean diameter of 0.1 micron and surface area of about 20000 m^2/kg or approximately 10 times more than Portland cement which fills almost all the pores in concrete. And also it reacts very fast with cement in the initial ages to produce a binder gel as similar to cement, hence there is no significant rise in percentage of water absorbed at 28 days and at 56 days of the concrete having SF.

The Fig. 4.18 shows that CM shows higher absorption i.e. 0.206 % at the age of 28 days and 0.396 % at the age of 56 days than that of SCC A, SCC B, SCC C i.e. 0.133 % and 0.230 % at the age of 28 and 56 days, 0.113 % and 0.150 % at the age of 28 and 56 days, 0.090 % and 0.110 % at the age of 28 and 56 days respectively, that means water absorption values of all the Self-compacting SF concretes were lower than the control mix, and the absorption decreased with an increase in percentage of silica fume replacement.

4.3.4. Shrinkage

From the results, it is obtained that increasing the amount of Silica fume results in a systematic reduction in shrinkage. At high SF content i.e. 12 % (SCC C) and in Control Mix there is a noticeable difference i.e. -0.025 to -0.058 cm in 5 days, -0.035 to -0.086 cm in 10 days, -0.049 to -0.113 cm in 15 days and -0.054 to -0.132 cm in 20 days, as given in Table 4.10 and Fig. 4.19.

Table 4.10: Shrinkage value at various ages

	Shrinkage value (cm)			
Mix	**5 days**	**10 days**	**15 days**	**20 days**
SCC A (4% SF)	-0.040	-0.066	-0.078	-0.084
SCC B (8% SF)	-0.036	-0.059	-0.070	-0.071
SCC C (12% SF)	-0.025	-0.035	-0.049	-0.054
CM	-0.058	-0.086	-0.113	-0.132

This happens because, In hardened concrete, silica-fume particles increase the packing of the solid materials by filling the spaces between the cement grains in much the same way as cement fills the spaces between the fine-aggregate particles, and fine-aggregate fills the spaces between coarse-aggregate particles in concrete.

The main effect on the pore structure is the reduction of large pores by blocking them with hydration products. The transformation of continuous pores into discontinuous pores has a profound effect on the permeability of silica-fume concrete.

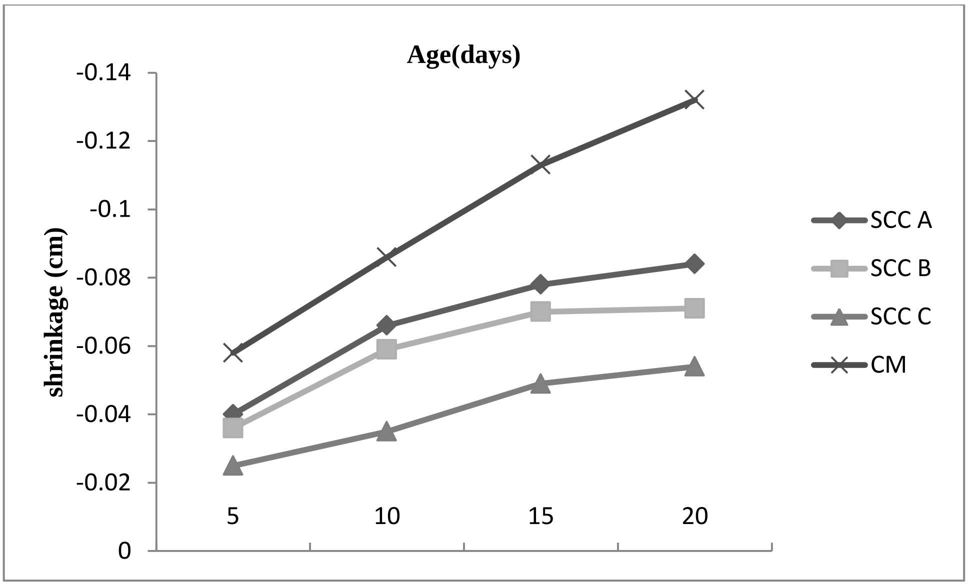

Fig.4.19: Shrinkage value at various ages.

4.3.5. Sorptivity

Sorptivity coefficient was determined by means of simple test allowing one face of concrete specimen in contact with water and the mass of water absorbed by capillary suction was measured at predefined intervals.

From the results (Table 4.11), it is obtained that increasing the amount of SF results in a systematic reduction in Sorptivity. At low SF content i.e. 4 % (SCC A) the water absorbed by capillary action is nearly less than Control Mix, but there is a noticeable difference in the capacity of water absorption by the capillary action between SCC C and Control Mix, the control mix has high sorption capacity of 0.00057 kg/cm^2 and the SCC C (12 % SF replacement) has 0.00028 kg/cm^2.However by using high amount of SF the Sorptivity decreases, as shown in Table 4.11 and Fig. 4.20.

Table 4.11: Evolution of water absorption by capillarity carried out with ages

	Water absorbed by capillarity (kg/cm^2)					
Mix	**15 min**	**30 min**	**1 hour**	**24 hours**	**48 hours**	**72 hours**
SCC A (4% SF)	0.00009	0.00011	0.00016	0.00024	0.00036	0.00051
SCC B (8% SF)	0.00004	0.00008	0.00014	0.00020	0.00024	0.00033
SCC C (12% SF)	0.00004	0.00008	0.00012	0.00017	0.0002	0.00028
CM	0.0001	0.0002	0.00025	0.00037	0.00047	0.00057

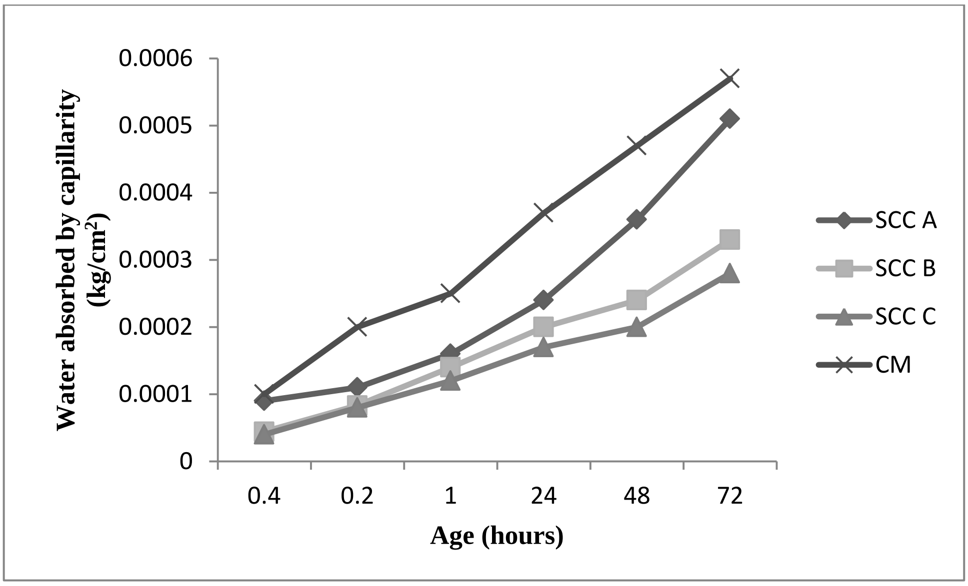

Fig.4.20: Evolution of Sorptivity carried out with ages.

In the same manner Pereira-de-oliveira et al. (2005) observed that the silica fume concrete gives a similar behaviour to the one of normal concrete and Turk et al. (2007) also observed the lowest Sorptivity value (0.2 ($x10^{-3}$) $cm/s^{1/2}$) from the SCC incorporated with SF. Therefore, with a proper curing as well as a pozzolanic admixture such SF as cement component can be enhance the resistivity of concretes against Sorptivity significantly.

4.3.6. Sulphate Resistance

The reduced permeability of silica- fume concrete would be expected to reduce the transport of sulfate ions into concrete. Since silica fume replacement levels are taken from 4% to 12%. The dilution effect on C_3A would be small. The main effect on the pore structure is the reduction of large pores by blocking them with hydration products. The transformation of continuous pores into discontinuous pores has a profound effect on the sulphate resistance of silica-fume concrete. The effect of silica fume on sulfate resistance is due more to the reduction in permeability than to dilution of the C_3A content because of the relatively low doses of silica fume. The most important factor to prevent external sulfate attack is to reduce the permeability of the concrete (low water/cement ratio, high cement content, well compacted and well cured). Hence usage of supplementary cementing materials increases the resistance against sulphate attack.

The Table 4.12 and Fig. 4.21 shows the percentage loss in weight of concrete specimens made by using various amount of replacements in cement quantity by SF with respect to age.

Table 4.12: Percentage of weight loss with ages

	Percentage loss in weight			
MIX	**3 days**	**7 days**	**14 days**	**21 days**
SCC A (4% SF)	-0.88	-1.22	-1.86	-3.48
SCC B (8% SF)	-0.68	-0.86	-1.62	-2.87
SCC C (12% SF)	-0.50	-0.58	-1.50	-2.67
CM	-2.70	-3.13	-5.20	-7.41

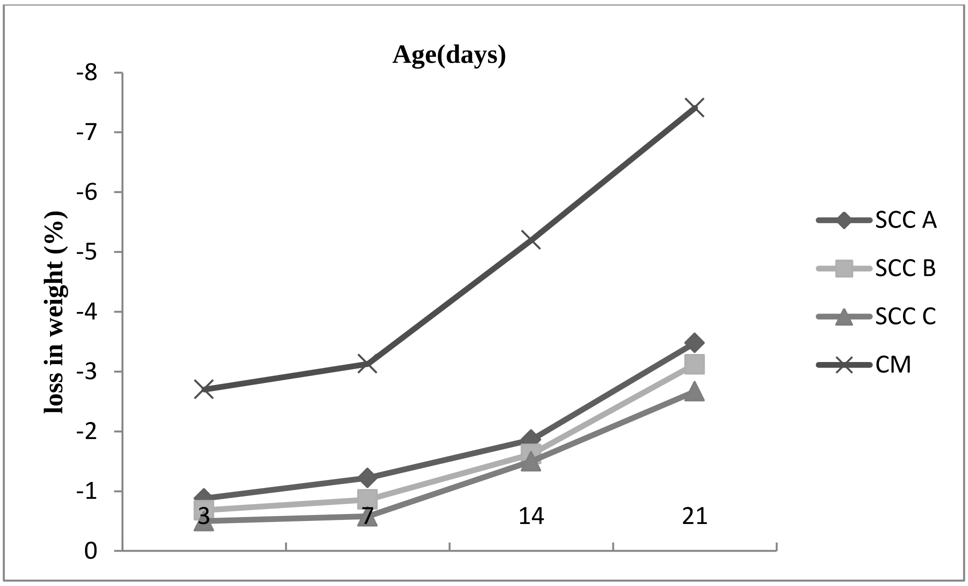

Fig.4.21: Percentage of weight loss with ages.

Here, as per results obtained, there is a remarkable loss in weight of Control Mix, as compare to SCC C. At the age of 3 days SCC C posses 0.50 % loss as compare to CM i.e. 2.70 %, at the age of 7 days SCC C losses 0.58 % as CM lost 3.13 % and by the last reading that is at the age of 21 days SCC C lost 1.50 % and CM lost 7.41 % of weight.

CONCLUSIONS

Following observations have been made from the study by using Fly ash:

- For 35% fly ash replacement, the fresh properties observed were good as compare to 15% and 25% fly ash replacement. Hence if we increase the FA replacement we can have a better workable concrete.
- An increase of about 24% strength at 28 days and 30% at 56 days was observed with the decrease of fly ash content from 35% FA to 15% FA.
- Absorption is mainly influenced by the paste phase primarily; it is dependent on the extent of interconnected capillary porosity in the paste. Concrete mixes with higher paste contents are bound to have higher absorption values than concretes with lower paste content, as observed 35% FA replacement shows higher absorption i.e. 2.67 % at the age of 28 days and 3.59 % at the age of 56 days than 15% FA replacement (0.46 % at the age of 28 days and 0.67 % at the age of 56 days).
- 35% FA replacement shows 2 times less shrinkage in 20 days than that of 0% FA replacement. From the results it is obtained that increasing the amount of fly ash results in a systematic reduction in shrinkage.
- Increasing the amount of fly ash results in a systematic reduction in Sorptivity, the 0% FA replacement has approximately 70 % high sorption capacity than 35% FA replacement.
- For sulfate resistance, there is a remarkable loss in weight of 0% FA replacement (CM), as compare 35% FA replacement (SCC3). At the age of 3 days, SCC3 posses 0.600 % loss as compare to CM i.e. 2.700 %, at the age of 7 days, SCC3 losses 0.437 % as CM lost 3.130 % and by the last reading that is at the age of 21 days SCC3 lost 3.931 % and CM lost 7.410 % of weight.

Following observations have been made from the study by using Silica Fume:

- SCCs with Silica Fume (SF) exhibited satisfactory results in workability, because of small particle size and more surface area.
- 4 to 8 percent by mass replacement of silica fume for cement gives the highest strength for short and long terms and when silica fume is replaced by 12% the strength decreases.

- 0% SF replacement shows higher absorption i.e. 0.206 % at the age of 28 days and 0.396 % at the age of 56 days than that of 4%, 8%, 12% i.e. 0.133 % and 0.230 % at the age of 28 and 56 days, 0.113 % and 0.150 % at the age of 28 and 56 days, 0.090 % and 0.110 % at the age of 28 and 56 days respectively, that means water absorption values of all the Self-compacting SF concretes were lower than the control mix, and the absorption decreased with an increase in percentage of silica fume replacement.
- Increasing the amount of Silica fume results in a systematic reduction in shrinkage. At high SF content i.e. 12 % SF replacement and in 0% SF replacement there is a noticeable difference i.e. -0.025 to -0.058 cm in 5 days, -0.035 to -0.086 cm in 10 days, -0.049 to -0.113 cm in 15 days and -0.054 to -0.132 cm in 20 days.
- Increasing the amount of SF results in a systematic reduction in Sorptivity. The 0% SF replacement has high sorption capacity of 0.00057 kg/cm^2 and the 12 % SF replacement has 0.00028 kg/cm^2.
- For sulfate resistance, there is a remarkable loss in weight of 0% SF replacement (CM), as compare to 12% SF replacement (SCC C) i.e. At the age of 3 days, SCC C posses 0.50 % loss as compare to CM i.e. 2.70 %, at the age of 7 days, SCC C losses 0.58 % as CM lost 3.13 % and by the last reading that is at the age of 21 days SCC C lost 1.50 % and CM lost 7.41 % of weight.

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