STRENGTH PROPERTIES AND SULPHATE RESISTANCE OF SELF-COMPACTING CONCRETE INCORPORATING SILICA FUME AND METAKOLIN

A thesis submitted in partial fulfilment of the requirements for the award of degree
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CERTIFICATE

This is to certify that the work presented in Thesis entitled “Strength properties and sulphtate resistance of self compacting concrete incorporating Silica fume and Metakolin” submitted by, **ANHAD SINGH GILL Roll No. 801022004** in partial fulfilment of the requirements for the award of **Masters 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. And 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. 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 investigate the strength properties (compressive strength and splitting tensile strength) and sulphate resistance of self compacting concrete made with Silica fume and Metakolin. For this purpose cement is replaced by weight in three different proportions of 5%, 10% and 15% by Silica fume and Metakolin respectively. Specimens are tested for compressive strength, splitting tensile strength and sulphate resistance. Testing is done at age of 7, 28 and 56 days.

Self compacting concrete made in this work by incorporating Silica fume and Metakolin passes all plasctic stage tests of SCC. Furthermore hardened stage tests (compressive strength and splitting tensile strength) results were also positive. There was increase of 18 – 38% compressive strength with incorporation of Silca fume and 15 – 45% increase with incorporation of metakolin. Also there was increase in sulphate resistance of SCC when cement is replaced by Silica fume and metakolin .

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1. Introduction

1.1 General

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.

Self compacting concrete is a concrete which compacts itself, there is no further compaction required for self compacting concrete. Development of self-compacting concrete (SCC) is a desirable achievement in the construction industry in order to overcome problems associated with cast-in-place concrete. Self compacting concrete is not affected by the skills of workers, the shape and amount of reinforcing bars or the arrangement of a structure and, due to its high-fluidity and resistance to segregation it can be pumped longer distances (Bartos, 2000).

The concept of self-compacting concrete was proposed in 1986 by professor Hajime Okamura (1997), but the prototype was first developed in 1988 in Japan, by professor Ozawa (1989) at the University of Tokyo. Self-compacting concrete was developed at that time to improve the durability of concrete structures. Since then, various investigations have been carried out and SCC has been used in practical structures in Japan, mainly by large construction companies. Investigations for establishing a rational mix-design method and self-compactability testing methods have been carried out from the viewpoint of making it a standard concrete. Self-compacting concrete is cast so that no additional inner or outer vibration is necessary for the compaction. It flows like “honey” and has a very smooth surface level after placing. With regard to its composition, self-compacting concrete consists of the same components as conventionally vibrated concrete, which are cement, aggregates, and water, with the addition of chemical and mineral admixtures in different proportions.

Self compacting concrete has been described as “the most revolutionary development in concrete construction for several decades”. Originally developed in Japan to offset a growing shortage of skilled labour, it has proved to be beneficial from the following points,

1. Faster construction,
2. Improved durability,
3. Reduction in site manpower,
4. Better surface finish,

5. Easier placing,
6. Safer working environment.

Usually, the chemical admixtures used are high-range water reducers (super plasticizers). Mineral admixtures are used as an extra fine material, besides cement, and in some cases, they replace cement.

1.2 History Behind Development Of Self Compacting Concrete

Making concrete structures without vibration, have been done in the past. For examples, placement of concrete under water is done by the use of tremie without vibration. Mass concrete, and shaft concrete can be successfully placed without vibration. But the above examples of concrete are generally of lower strength and difficult to obtain consistent quality. Modern application of self-compacting concrete (SCC) is focussed on high performance, better and more reliable and uniform quality.Self-compacting concrete, in principle, is not new. Early self-compacting concretes relied on very high contents of cement paste and, once superplasticizers became available, they were added in the concrete mixes. The mixes required specialized and well-controlled placing methods in order to avoid segregation, and the high contents of cement paste made them prone to shrinkage. The overall costs were very high and applications remained very limited.

The introduction of “modern” self-leveling concrete or self-compacting concrete (SCC) is associated with the drive towards better quality concrete pursued in Japan around 1983, where the lack of uniform and complete compaction had been identified as the primary factor responsible for poor performance of concrete structures (Dehn et al., 2000). Due to the fact that there were no practical means by which full compaction of concrete on a site was ever to be fully guaranteed, the focus therefore turned onto the elimination of the need to compact, by vibration or any other means. This led to the development of the first practicable SCC by researchers Okamura and Ozawa, around 1986, at the University of Tokyo and the large Japanese contractors (e.g. Kajima Co., Maeda Co., Taisei Group Co., etc.) quickly took up the idea. The contractors used their large in-house research and development facilities to develop their own SCC technologies. Each company developed their own mix designs and trained their own staff to act as technicians for testing on sites their SCC mixes. A very important aspect was that each of the large contractors also developed their own testing devices and test methods (Bartos, 2000).

In the early 1990’s there was only a limited public knowledge about SCC, mainly in the Japanese language. The fundamental and practical know-how was kept secret by the large corporations to maintain commercial advantage. The SCCs were used under trade names, such as the NVC (Non-vibrated concrete) of Kajima Co., SQC (Super quality concrete) of Maeda Co. or the

Biocrete (Taisei Co.). Simultaneously with the Japanese developments in the SCC area, research and development continued in mix-design and placing of underwater concrete where new admixtures were producing SCC mixes with performance matching that of the Japanese SCC concrete (e.g. University of Paisley / Scotland, University of Sherbrooke / Canada) (Ferraris, 1999).

1.3 Motive for Development of Self-Compacting Concrete

Recognising the lack of uniformity and complete compaction of concrete by vibration, researchers at the University of Tokyo, Japan, started in late 1980's to develop Self compacting concrete. By the early 1990's, Japan has developed and used SCC that does not require vibration to achieve full compaction. By the year 2000, the SCC has become popular in Japan for prefabricated products and ready mixed concrete. The utilisation of self compacting concrete started growing rapidly.

The other 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. Studies to develop self-compacting concrete, including a fundamental study on the workability of concrete, were carried out by researchers Ozawa and Maekawa (Bartos, 2000) at the University of Tokyo.

During their studies, they found that the main cause of the poor durability performances of Japanese concrete in structures was the inadequate consolidation of the concrete in the casting operations. By developing concrete that self-consolidates, they eliminated the main cause for the poor durability performance of the concrete. By 1988, the concept was developed and ready for the first real-scale tests and at the same time the first prototype of self-compacting concrete was completed using materials already on the market. The prototype performed satisfactorily with regard to drying and hardening shrinkage, heat of hydration, denseness after hardening, and other properties and was named "High Performance Concrete."

At almost the same time, "High Performance Concrete" was defined as a concrete with high durability due to low water-cement ratio by professor Aitcin (Ouchi et al., 1996). Since then, the term high performance concrete has been used around the world to refer to high durability concrete. Therefore, Okamura (1997) has changed the term for the proposed concrete to "Self-Compacting High Performance Concrete."

1.4 More about self compacting concrete

Self compacting concrete 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 flowability of SCC makes it possible to fill the formwork without vibration (Khayat et al., 2004).

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 et al.,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:

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

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 compactibility 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: (1) SCC may have a lower modulus of elasticity, which may affect deformation characteristics of prestressed concrete members and (2) 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 a 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.

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.

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, 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 fulfill other construction needs because its production has taken into consideration the requirements in the structural design.

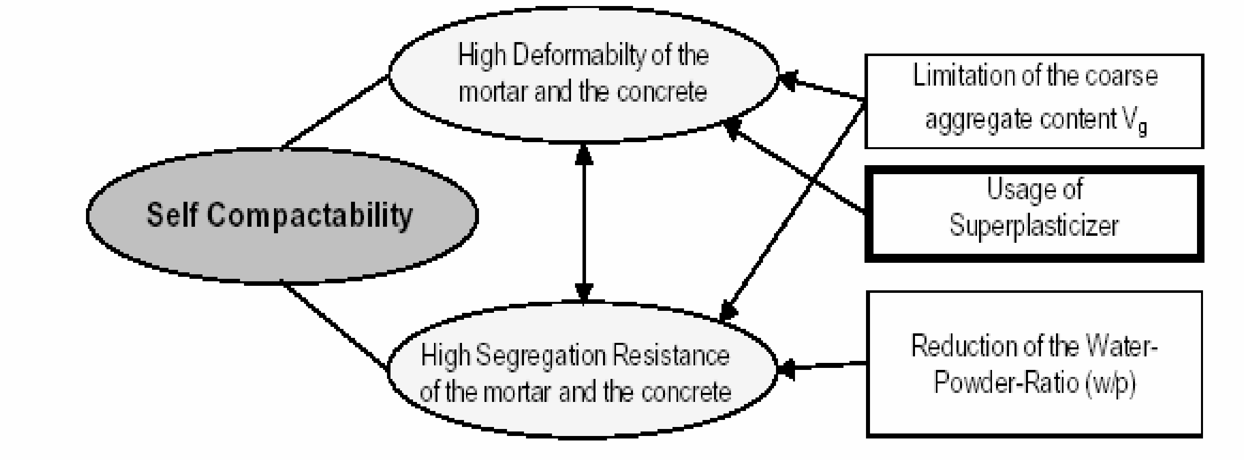

Fig. 1.1: Basic principles for the production of SCC (Dehn et al., 2000).

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1.5 World-wide Current Situation of Self-Compacting Concrete

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/Prestressed Concrete Institute (PCI) which has done some research on the use of SCC in precast/prestressed concretes starting with 1999 (Bartos, 2000). It is estimated that the daily production of SCC in the precast/prestressed industry in the United States will be 8000 m3 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.

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 et al., 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 tunneling, 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 - year 2003 - there is no universally adopted standardized test method for evaluation of self-compactability 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.

1.6 Advantages And Disadvantages Of SCC

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 labor, 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):

i. Faster construction,
ii. Reduction in site manpower,
iii. Easier placing,
iv. Uniform and complete consolidation,
v. Better surface finishes,
vi. Improved durability,
vii. Increased bond strength,
viii. Greater freedom in design,
ix. Reduced noise levels, due to absence of vibration, and
x. Safe working environment.

Because compaction is eliminated, the internal segregation between solid particles and the surrounding liquid is avoided which results in less porous transition zones between paste and aggregate and a more even colour of the concrete . Improved strength, durability and finish of SCC can therefore be anticipated

Very good finish effect can be achieved of a pure SCC cement placed in a steel mould, de-moulded after 24h after casting. The surface is so smooth and dense that it can reflect light.

For much concrete construction, the structural performance is improved by increasing reinforcement volumes, limiting cracking by using smaller bar diameters and using complex formwork, all of which increase the difficulty of compaction (Okamura et al., 2003). Self compacting concrete meets the above developments by making casting homogeneous concrete in congested structures possible; it also improves efficiency and effectiveness on site by reducing the construction time and labour cost.

SCC requires higher powder and admixture (particularly super plasticisers) contents than NVC and so the material cost is higher (The Concrete Society and BRE, 2005). It was reported that in most cases, the cost increase ranged from 20% to 60% compared to similar grade NVC (Nehdi et al., 2004;). However, in very large structures, increased material cost by using SCC was out weighed by savings in labour costs and construction time.

1.7 Need For This Research

SCC has not gained much local acceptance though it has been promoted in the Middle East for the last five years. Awareness of SCC has spread across the world, prompted by concerns with poor consolidation and durability in case of conventionally vibrated Normal concrete. The reluctance in utilizing the advantages of SCC is,

1. Lack of research or published data pertaining to locally produced SCC.
2. The potential problems for the production of SCC, if any, with local marginal aggregates and the harsh environmental conditions prevailing in the region.

Therefore, there is a need to conduct studies on SCC.

1.8 Mineral Admixtures

1.8.1 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. 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 SiO2). Condensed silica fume has a surface area of about 20,000 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 pozzolan, 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. 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.

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. The use of silica fume generally aids the pump ability of concrete and is most effective in lean mixtures. Because of its containing silica fume may exhibit an increase in plastic shrinkage cracking concrete is protected against drying bleeding characteristics, concrete. The problem may be avoided by ensuring that such, both during and after 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 1.1 : Physical Properties of Silica Fume (khayat,and 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

Table 1.2: Chemical composition of Silica Fume (khayat, and 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

1.8.2 Metakolin

Metakaolin is an artificial pozzolana produced by burning selected kaolinite clay within a specific temperature range (between 650 and 800 _C). When heated to 700–900 _C, kaolin becomes calcined, losing up to 14% hydroxyl water and changing into MK (Caldarone et al., 1994). Because the production of MK can be closely controlled, a higher degree of purity and pozzolanic reactivity can be obtained with proper quality control (Kostuch et al., 1993). MK is basically made up of silica and alumina in an amorphous state, that react with calcium hydroxide (CH) produced by Portland cement hydration to form calcium hydrosilicate (C–S–H) and calcium hydroaluminosilicate (essentially gehlenite – C2ASH8). There is a consensus in the literature that the pozzolanic reaction between MK and CH helps to refine the binder capillary porosity, with the direct consequence of improving the mechanical characteristics mainly at early ages, and durability e.g. resistance to sulfate attack ,chloride ingress and alkali silica reaction. The permeability, scaling resistance, chemical resistance, and freezing and thawing durability of the MK concrete mixture were similar or slightly better than those of the SF mixture (Zongin et al. 1999). Improvement in other aspects of durability such as sulfate resistance, rapid chloride ion permeability, and expansion due to alkali- silica reaction are also confirmed in MK mixtures (with increased MK replacement levels of up to 25%) compared with control and SF mixtures (khatib et al., 1998). The chemical and physical properties of metakolin are given below in Table 1.3.

Table 1.3 : Chemical and physical properties of metakolin (Guneyisi et al., 2010)

Constituents	**Percent**
CaO	0.78
SiO_2	52.68
Al_2O_3	36.34
Fe_2O_3	2.14
MgO	0.16
SO_3	-
K_2O	0.62
Na_2O	0.26
LOI	0.98
Specific Gravity	2.5
BET Fineness (m^2/kg)	12000

2. Tests And Properties

2.1 Properties

Fresh SCC must possess at required levels the following key properties:

Filling ability: This is the ability of the SCC to flow into all spaces within the formwork under its own weight.

Passing ability: This is the ability of the SCC to flow through tight openings such as spaces between steel reinforcing bars, under its own weight.

Resistance to segregation: The SCC must meet the required levels of properties A & B whilst its composition remains uniform throughout the process of transport and placing.

2.2 Tests

Some of the important tests conducted on fresh SCC to evaluate its workability are summarized under in a table and are briefly explained later.

Table 2.1 : Test methods to evaluate the workability properties of SCC (EFNARC, 2002).

Property	Test Methods	
	Laboratory (Mix Design)	Field (Quality Control)
Filling Ability	Slump Flow Test T_{50cm} Flow Test V-Funnel Test Orimet Test	Slump Flow Test T_{50cm} Flow Test V-Funnel Test Orimet Test
Passing Ability	L- Box Test U- Box Test Fill Box Test	J-Ring Test
Segregation Ressistance	GTM Test V-Funnel At T_{5mins}	GTM Test V-Funnel At T_{5mins}

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). This test is used to measure the filling ability of SCC. The apparatus consists of a vessel that is divided by a middle wall into two compartments. It provides a good direct assessment of passing ability.

For conducting the U-box test, one of the compartments of the apparatus is filled with the concrete sample and filled concrete is left to stand for 1 minute. Then the sliding gate is lifted to allow the concrete to flow out into the other compartment. After the concrete comes to rest, the height of the concrete in the compartment that has been filled is measured in two places and the mean height (H1) is calculated. Also the height in the other compartment (H2) is measured. The filling height is then calculated as H1- H2. The whole test has to be performed within 5 minutes. If the concrete flows as freely as water, at rest it will be horizontal, so H1- H2 = 0. Therefore, the nearer this test value, i.e., the filling height', is zero, the better the flow and passing ability of SCC (EFNARC, 2002).

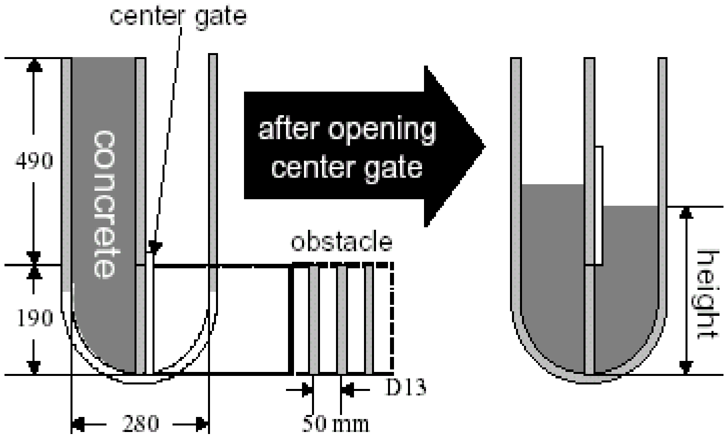

Fig. 2.1 : U-type test (Ouchi et al., 2000)

Slump Flow test: The slump flow test is used to assess the horizontal free flow of SCC in the absence of obstructions. The basic equipment used is the same as for the conventional Slump test. The test method differs from the conventional one by the fact that the concrete sample placed into the mold 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 (EFNARC, 2002).

Fig. 2.2 : Slump flow test (Zhimin et al.,2008)

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.

L-Box test: This method uses a test apparatus comprising of a vertical section and a horizontal trough into which the concrete is allowed to flow on the release of a trap door from the vertical section passing through reinforcing bars placed at the intersection of the two areas of the apparatus (Dietz et al., 2000). The time that it takes the concrete to flow a distance of 200mm and 400mm into the horizontal section is measured, as is the height of the concrete at both ends of the apparatus (H1 & H2). The L-Box test can give an indication as to the filling ability and passing ability.

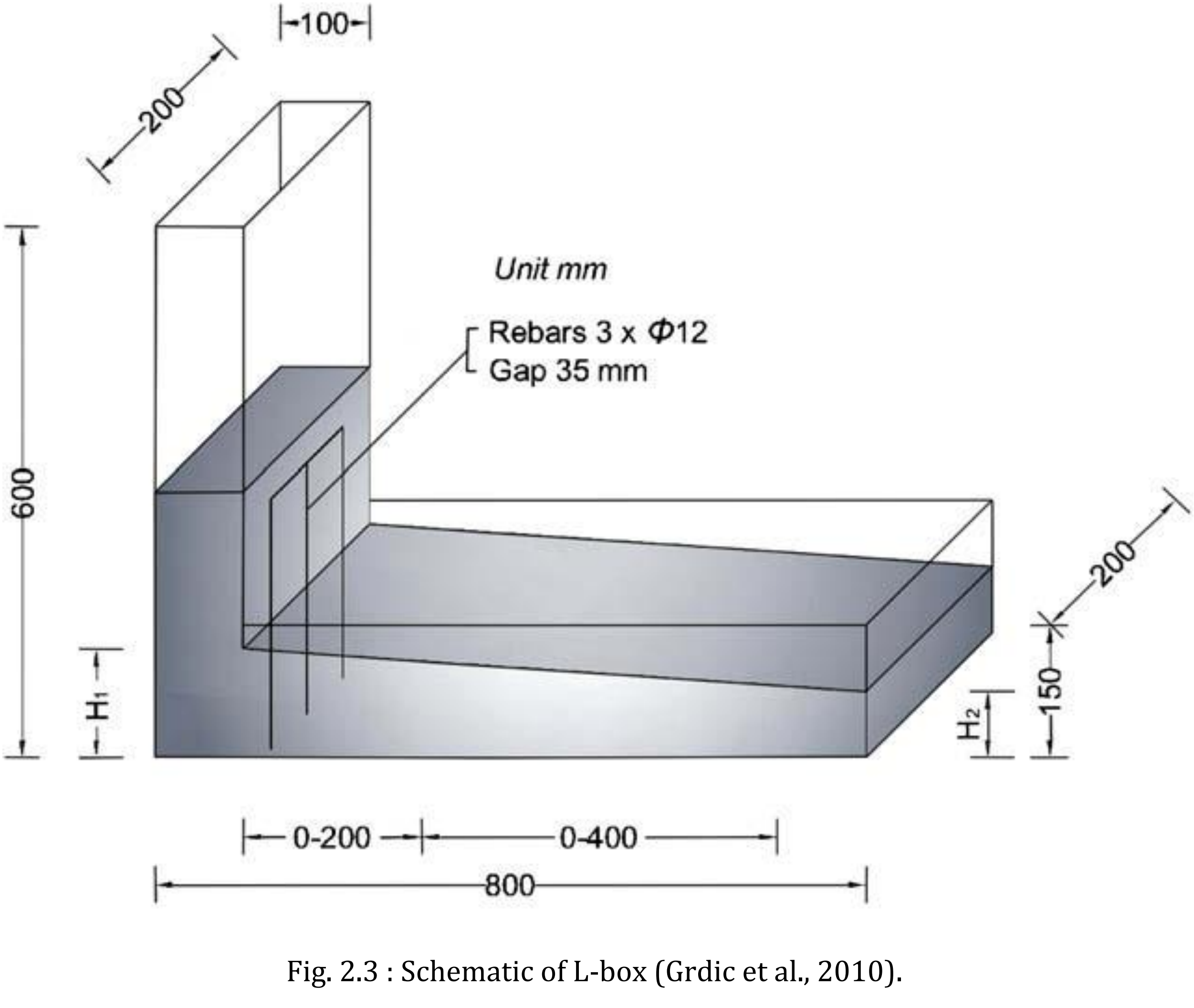

Fig. 2.3 : Schematic of L-box (Grdic et al., 2010).

Fig. 2.4 : L-box (Google – Images for SCC)

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 (Bartos, 2000). 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).

V-funnel test: Viscosity of the self-compacting concrete is obtained by using a V-funnel apparatus, which has certain dimensions (Fig. 2.5), in order for a given amount of concrete to pass through an orifice (Dietz et al., 2000). The amount of concrete needed is 12 liters and the 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.

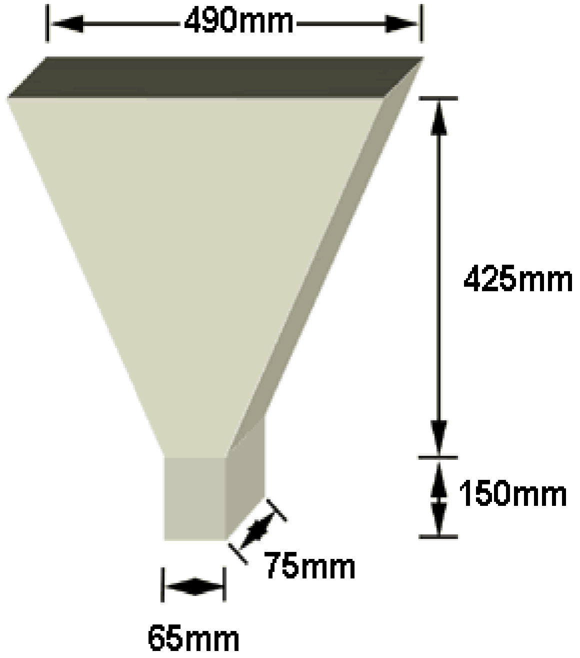

Fig 2.5 : V-funnel (Dietz et al., 2000)

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.

Slump Flow/J-Ring combination test: This test (Fig. 2.6) 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.

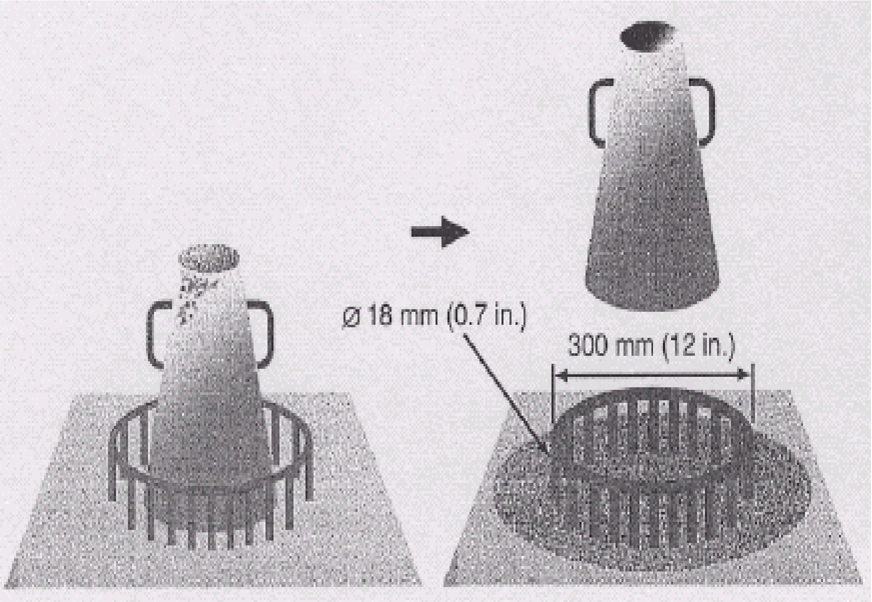

Fig. 2.6 : Slump Flow/J-Ring combination test (Kosmatka et al., 2002)

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

The size and quantity of coarse aggregates in a SCC mixture are directly related to the concrete passing ability. The passing ability requirements depend on the formwork geometry and the extent of congestion of the reinforcement. Risk of blockage is reduced by providing adequate viscosity.

Adequate cohesiveness can be obtained by incorporating a viscosity-modifying admixture (VMA) along with a high range water reducing admixture to control bleeding, segregation, and surface settlement (Khayat et al., 1997).

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

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

Method	Unit	Minimum Value	Maximum Value
Slump flow	mm	650	800
J –Ring	mm	0	10
V- Funnel	sec	6	12
L-Box	(H2/H1)	0,8	1,0
U- Box	(H2-H1)mm	0	30
Orimet	sec	O	5
Fill Box	%	90	100

3. LITERATURE REVIEW

As already discussed self compacting concrete posses many advantages over the normal concrete. Elimination of vibration for compacting concrete during placing through the use of Self Compacting Concrete leads to substantial advantages related to better homogeneity, enhancement of working environment and improvement in the productivity by increasing the speed of construction . Understanding of this concrete flow property is of interest to many researchers.

Self-compacting concrete extends the possibility of use of various mineral by-products in its manufacturing and with the densification of the matrix, mechanical behavior, as measured by compressive, tensile and shear strength, is increased. On the other hand, the use superplasticizers or high range water reducers, improves the stiffening, unwanted air entrainment, and flowing ability of the concrete. Practically, all types of structural constructions are possible with this concrete.

In this section we will study of some of previous work done by researchers on some of key properties of self compacting concrete.

3.1. Fresh Concrete Properties

Kou And Poon (2009) studied fresh properties such as flowabilty, passing abilty, segregation resistance of self compacting concrete using recycled fine and coarse aggregates. They prepared three series of SCC mixtures with different fine recycled aggregate contents as replacement of river sand and water-to-binder (W/B) ratios. The SCC mixtures were prepared with 0, 25, 50, 75 and 100% fine recycled aggregates, the corresponding water-to-binder ratios (W/B) were 0.53 and 0.44 for the SCC mixtures in Series I and II, respectively. In series III, three different W/B ratios of 0.44, 0.40, and 0.35 were used. Ordinary Portland cement (with a fineness of 3520 cm^2/g and density of 3150 kg/m^3 respectively) and fly ash (FA) were used as the cementitious materials in the SCC mixtures. Proportion of cement in all thre series is 340 kg/m^3. Two types of fly ash was used, the first one was a fine fly ash (f-FA) (not used in series I) which complied with BS 3892 with most of the particles passing through the 45 µm sieve (Used proportion 70 kg/m^3). The other one was the rejected fly ash (r-FA) with most of the particles >45 µm (Used proportion 200 kg/m^3). The chemical admixtures used were a superplasticizer (Grace, ADVA-109) and a viscosity agent (Grace, V -MAR 2) commercially available in Hong Kong. Slump flow test, GTM screen stabity test and L-box tests were conducted and their result is given in Table 3.1 below.

It is evident from Table 3.1 that the slump flow diameter increased with an increase in the fine recycled aggregate content. This was attributed to the high water absorption capacity of the fine recycled aggregates compared to river sand. From Table 3.1 it can be seen that the blocking ratio varied from 0.85 to 0.93 for the RA-SCC mixtures in Series I. The blocking ratio was between 0.87 and 0.94 for the RA-SCC mixtures in Series II. Furthermore, the blocking ratio of the RA-SCC mixtures in Series III was between 0.87 and 0.94 as the W/B ratio decreased from 0.44 to 0.35. The results indicated that the RA-SCC mixtures prepared in this study achieved adequate passing ability and maintained sufficient resistance to segregation.

Table 3.1 : Fresh properties of RA-SCC mixtures in Series I, II and III (Kou And Poon, 2009)

Mix code	Initial slump flow	Slump flow (after 1h)	Slump loss (%)	Segregation ratio (%)	L – box test		Wet density (Kg/m^3)
	Diameter (mm)	Diameter (mm)			Ratio (%)	Time (s)	
Series I							
Control - 1	760	740	2.6	8.9	0.85	36.3	2220
RF25	765	735	3.9	9.1	0.87	29.5	2210
RF50	775	730	5.8	9.5	0.90	20.5	2200
RF75	785	725	7.6	10.3	0.91	25.1	2170
RF100	795	715	10.1	11.1	0.93	23.8	2170
Series II							
Control - 2	820	800	2.4	10.3	0.87	23	2200
RF25	825	795	3.6	10.4	0.89	20.4	2160
RF50	835	785	6.0	10.6	0.91	20.7	2140
RF75	845	775	8.3	10.3	0.92	14.7	2120
RF100	860	770	10.4	9.9	0.94	13.4	2140
Series III							
RF100A	860	770	10.4	9.9	0.94	13.4	2140
RF100B	810	750	7.4	10.8	0.94	27.0	2180
RF100C	795	735	7.5	10.2	0.87	18.7	2150

Uysal And Sumer (2011) conducted fresh properties tests such as slump flow, T_{50}, and L- box on self compacting concrete replacing portland cement with different mineral admixtures. They prepared sixteen series of mix proportions, of which one is control, and fifteen were prepared by replacing portland cement (specific surface area 399.6 m^2/kg) with fly ash (FA)(15%, 25% and 35%) (proportion used is 83, 138, 193 kg/m^3 respectively) granulated blast furnace slag

(GBFS)(20%, 40% and 60%) (110, 220, 330 kg/m^3 respectively) limestone powder (LP)(10%, 20% and 30%) (55, 110 165 kg/m^3 respectively), basalt powder (BP)(10%, 20% and 30%) (55, 110, 165 kg/m^3 respectively) and marble powder (MP)(10%, 20% and 30%) (55, 110, 165 kg/m^3 respectively). A natural river sand and crushed limestone with a maximum size of 16 mm was used as fine and coarse aggregates respectively. The total powder content was fixed to 550 kg/m^3 and the water–powder ratio (w/p) was selected as 0.33. Test results are depicted blow in Fig. 3.1, 3.2 and 3.3.

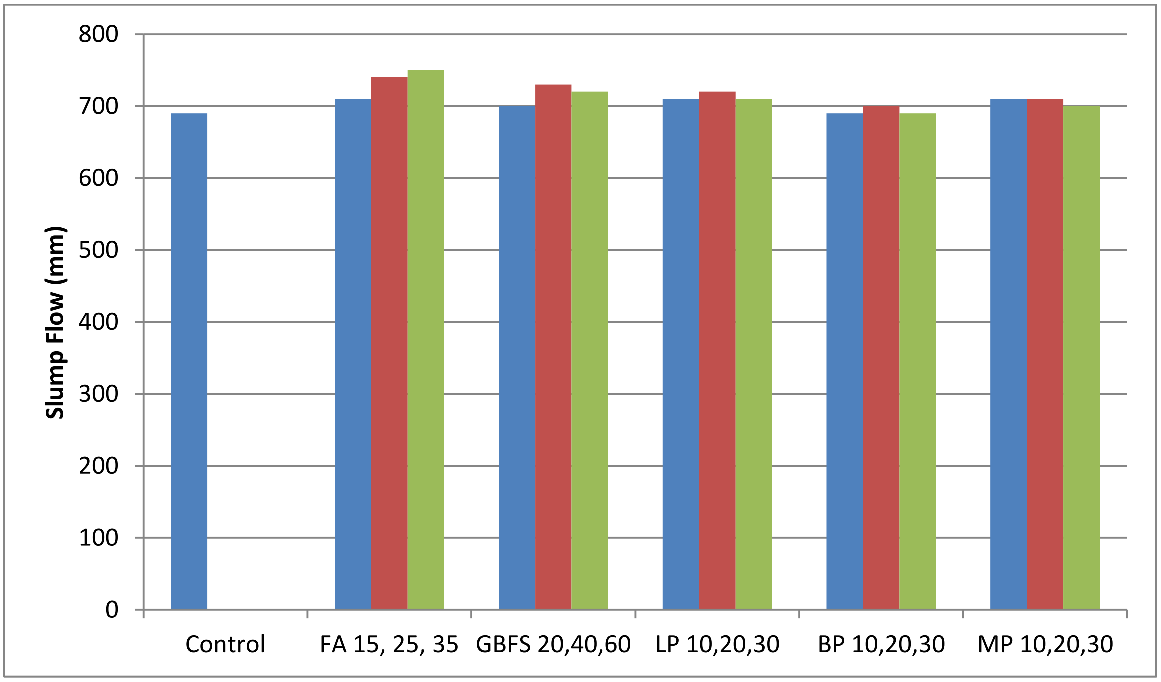

Fig. 3.1 : Slump-flow values (Uysal And Sumer, 2011)

In terms of slump flow, all SCC mixtures exhibited satisfactory slump flows in the range of 690–750 mm, which is an indication of a good deformability. The slump flow time for the concrete to reach diameter of 50 cm (T50) for all the mixtures was less than 5 s and all SCC mixtures showed flow time values in the range of 2–5 s. Both the slump-flow values and the T_{50} times are in good agreement to that of the values given by European guidelines for range of applications.

L-box test (time taken to reach 400 mm distance (T_{400}), time taken to reach 800 mm distance (T_{800}) and the ratio of heights at the two edges of L-box) represents the filling and passing ability of SCC. In L-box test blocking ratio (h2/h1) must be between 0.8 and 1.0. L-box tests are depicted above in figure 11. All the mixtures of SCC have remained in target range which is as per EFNARC standards.

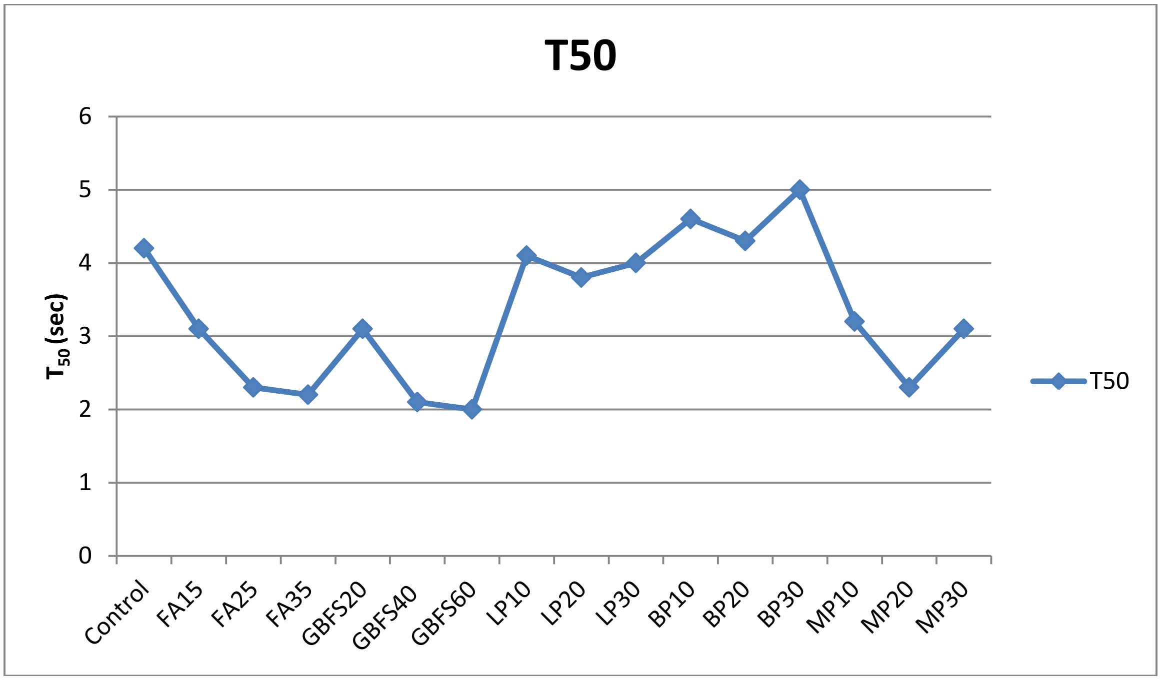

Fig. 3.2 : T_{50} time of SCC mixes .(Uysal And Sumer, 2011)

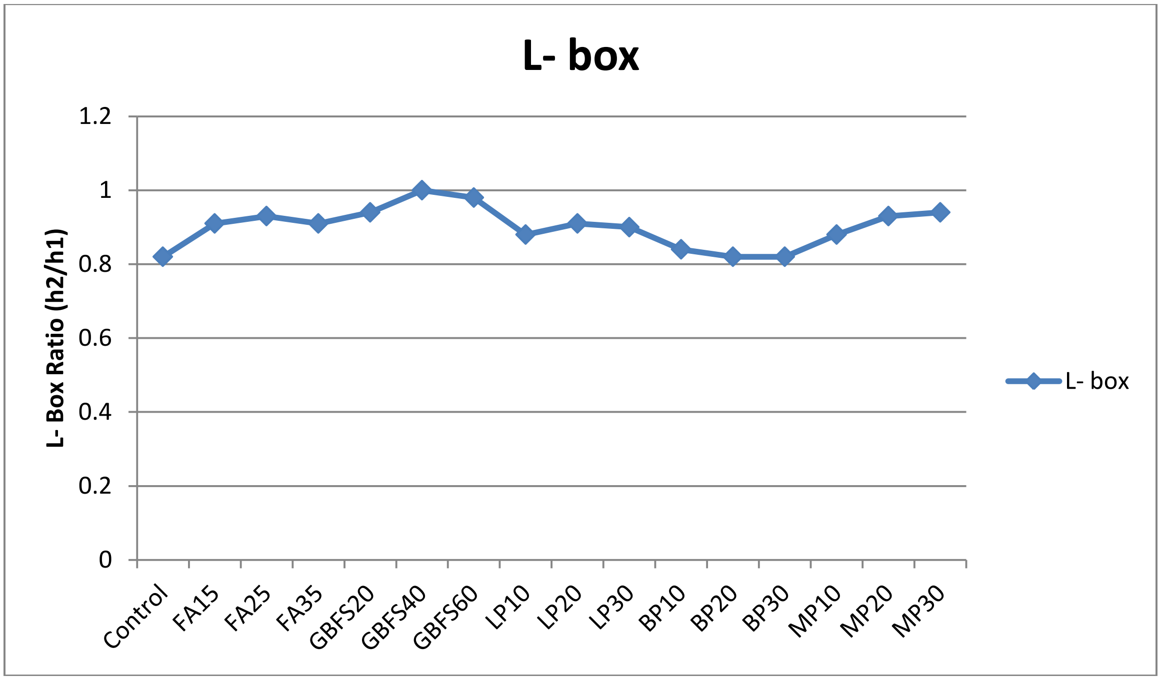

Fig. 3.3 : L-box ratio of SCC mixtures. (Uysal And Sumer, 2011)

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 ultra pulverized fly ash of total cementitious material and sand was replaced by broken gravels. Super-plasticizer content is 1.0-1.6 % of total cementitious material for water content of 175 l/m^3. When the super-plasticizer 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%.

Siddique (2010) performed the various tests and reported results of various fresh properties of self compacting concrete. The various tests conducted were slump flow test (slump flow diameter and T_{50}cm), J-ring test (flow diameter and difference in concrete height inside and outside J-ring (h2–h1)), L-box test (time taken to reach 400 mm distance T_{400mm}, time taken to reach 600 mm distance T_{600mm}, and time taken to reach 800 mm distance T_{800mm}, ratio of heights at the two edges of L-box (H_2/H_1), V-funnel test (time taken by concrete to flow through V-funnel after 10 sec T_{10s}, time taken by concrete to flow through V-funnel after 5 min T_{5min}), U-box test (difference in height of concrete in two chambers (H2–H1)) for various mix compositions of SCC incorporating fly ash. The mixes were prepared with five percentages of class F fly ash (15%; 85 kg/m^3, 20%; 110 kg/m^3, 25%; 135 kg/m^3, 30%; 165 kg/m^3 and 35%; 195 kg/m^3 respectively). Proportions of cement are 465, 440, 415, 385 and 255 kg/m^3 respectively. A polycarboxylic ether based superplasticizer complying with ASTM C 494 type F, with density approximately 1.10 and pH approximately 5.0 was used. The various test results were given below in Table 3.2. 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 s.

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. 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. V-funnel flow time is the elapsed time in seconds between the opening of the bottom outlet depending upon the time after which opened (T_{10}s and T_{5min}) and the time when the light becomes visible from the bottom, when observed from the top. 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 H_2/H_1 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 3.2 : Fresh properties of SCC mix. (Siddique, 2010)

Mix	Slump Flow		j-Ring		V-funnel		L-Box				U-box
	Dia. (mm)	T_{50cm} (s)	Dia (mm)	h2–h1 (mm)	T_{10s} (s)	T_{5min} (s)	T_{400mm} (s)	T_{600mm} (s)	T_L (s)	(H2/H1)	(H1–H2) (mm)
SCC1	673.3	4.5	586.7	2.3	7.5	15.0	3.5	8.3	11.9	0.89	20
SCC2	690.0	3.0	580.0	6.7	4.5	5.1	1.4	2.4	3.5	0.95	10
SCC3	603.3	4.4	540.3	37.0	5.2	7.6	0.5	1.3	2.4	0.85	40
SCC4	673.3	3.0	626.7	3.0	6.1	9.5	1.2	2.2	4.0	0.95	5
SCC5	633.3	4.0	556.3	7.0	10.0	18.5	2.8	4.8	6.9	0.92	20

Grdic et al. (2010) conducted tests such as slump-flow test for flowability and viscosity, L-box test for testing passing ability and sieve segregation test for testing the segregation resistance of self compacting concrete using recycled aggregates in place of coarse aggregates in various percentages (0% , 50% and 100%). For making of concrete mixture the fractions of 0/4, 4/8 and 8/16 mm of the river aggregate were used, and the fractions 4/8 and 8/16 of recycled aggregate. Test results are given below in Table 3.3. From table it can be seen that slump flow test the distribution, in all three cases, amounted to 73 cm which ranks all the designed mixtures in the SF2 class which is the most common class in civil engineering usage and practice. For SF2 class, the T_{500} results should be in interval of 3.5–6.0 s. All the mixtures matched this requirement. No segregation or water separation was observed. All the mixtures meet the criterion that the ration of heights of concrete at the ends of L-box is no less then 0.8. The results demonstrate that all mixtures were resistant to segregation.

Table 3.3 : Test results obtained by measurement of fresh concrete (Grdic et al., 2010)

Type of concrete	Density (kg/m^3)	Slump floe test (cm)	T_{500} (s)	L-box test	Sieve segregation (%)	Wc (water–cement factor)
E	2391	73.5	5.60	0.94	11.7	0.41
P50	2366	73.5	5.40	0.95	9.31	0.43
P100	2355	72.5	6.00	0.98	5.2	0.45

Gesog˘lu et al. (2009) conducted various tests such as slump flow time, L-box height ratio, and V-funnel flow time to study fresh properties of self compacting concrete. A total of 22 concrete mixtures were designed having a constant water/binder ratio of 0.44 and a total binder content of 450 kg/m^3. The control mixture included only a Portland cement (PC) as the binder while the remaining mixtures incorporated binary, ternary, and quaternary cementitious blends of PC, fly ash (FA), ground granulated blast furnace slag (S), and silica fume (SF). { Meaning of binary, ternary and quaternary is : binary (PC + FA. PC + S, PC + SF), ternary (PC + FA + S, PC + FA + SF, and PC + S + SF) and quaternary (PC + FA + S + SF)}. The replacement levels for both FA and S were 20%, 40% and 60% while those of SF were 5%, 10% and 15% by weight of cement. Proprtion of cement used ranges from 180 to 450 kg/m^3 for different mixtures. Proportions of fly ash, ground granulated blast furnace slag and silica fume are in range of 0 – 270 kg/m^3, 0 – 270 kg/m^3 and 0 – 67.5 kg/m^3 respectively. Result of tests are given below in Table 3.4.

All of the concrete mixtures were designed to give a slump flow diameter of 70 +- 3 cm which was achieved by using superplasticizer at varying amounts. As seen in Table 3.4 that the slump flow diameter of the concretes ranged from 67 to 73 cm conforming EFNARC recommendations. Similarly, slump flow time was always lower than 5 s for all of the concretes meeting the upper limit of EFNARC. The L-box test showed that apart from the control mixture, the mixtures, each of which having binary blends of cementitious materials, and mixture containing 45% FA and 15% SF did not satisfy the lowest H2/H1 ratio of 0.8 recommended by EFNARC. As it is clearly observed in Table 3.4 that, however, all of the concretes made with ternary and quaternary blends of supplementary cementitious materials had H2/H1 ratios of 0.82–0.93 meeting the EFNARC limitations. Therefore, the combined use of the mineral admixtures in ternary and quaternary blends remarkably improved the filling and passing ability of the SCCs. The time measured using the V-funnel was in the range of 3.2– 17.4 s depending mainly on the mineral admixture used. The lowest V-funnel flow time of 3.2 s was measured for the control concrete while the mixture with 40% S had the highest flow time of 14 s.

Incorporating SF or S in binary system generally made the concretes more viscous. However, using FA beyond 20% replacement level decreased the viscosity which in turn resulted in much lower V-funnel flow time of the concretes. It was observed in Table 3.4 that all of the concretes incorporating any of the ternary cementitious blends generally satisfied the EFNARC limitations not only for the V-funnel flow time but also L-box height ratio and slump flow time.

Table 3.4 : Fresh properties of SCC (Gesoğlu et al., 2009)

Mix	Slump flow		L-Box	V-funnel flow time (s)
	T_{50} (s)	D (cm)	H_2/H_1	
Control - PC	1.0	67.0	0.706	3.2
20FA	2.0	67.5	0.706	10.4
40FA	2.0	73.0	0.800	6.0
60FA	1.0	72.0	0.950	4.0
20S	3.0	67.0	0.704	10.0
40S	3.0	71.0	0.706	14.0
60S	3.0	70.5	0.732	12.0
5SF	5.0	67.0	0.732	10.0
10SF	4.0	68.0	0.824	10.0
15SF	4.0	69.5	0.918	10.0
15FA5SF	3.0	69.0	0.844	7.5
30FA10SF	2.0	69.5	0.892	6.0
45FA15SF	3.0	72.0	0.791	6.0
15S5SF	4.0	68.0	0.929	8.0
30S10SF	3.0	71.5	0.824	5.2
45S15SF	3.8	70.5	0.824	11.2
10FA10S	3.0	70.5	0.854	9.9
20FA20S	2.2	69.0	0.859	6.6
30FA30S	3.0	73.0	0.904	6.2
7.5FA7.5S5SF	3.4	67.5	0.871	6.0
15FA15S10SF	2.8	67.5	0.851	4.9
22.5FA22.5S15SF	2.8	70.0	0.869	4.2
Acceptance criteria of SCC suggested by ERNARC				
Minimum	2.0	65.0	0.8	6.0
Maximum	5.0	80.0	1.0	12.0

Boukendakdji et al. (2011) studied the results of an experimental investigation carried out to study the effect of granulated blast furnace slag and two types of superplasticizers on the properties of self-compacting concrete (SCC). In control SCC, cement was replaced with 10%, 15%, 20%, and 25% of blast furnace slag. Two types of superplasticizers: polycarboxylate based superplasticizer and naphthalene sulphonate based superplasticizers were used. Tests were conducted for slump flow, the modified slump test, V-Funnel, J-Ring, U-Box, and compressive strength. The results showed that polycarboxylate based superplasticizer concrete mixes give more workability and higher compressive strength, at all ages, than those with naphthalene sulphonate based superplasticizer. Inclusion of blast furnace slag by substitution to cement was found to be very beneficial to fresh self-compacting concrete. An improvement of workability was observed up to 20% of slag content with an optimum content of 15%. Workability retention of about 45 min with 15% and 20% of slag content was obtained using a polycarboxylate based superplasticizer; compressive strength decreased with the increase in slag content, as occurs for vibrated concrete, although at later ages the differences were small.

Kathirvel et al. (2010) studied fresh properties of SCC with partial replacement of cement by Quarry and limestone (dust) powder. They replaced Ordinary portland cement (53 Grade) 10%, 20% and 30% by limestone powder and quarry dust respectively. Limestone powder with particle size less than 0.125 mm having a specific gravity of 2.53 was used. The specific gravity of crusher dust is 2.30. Mix proportions of cement and filler is 214.24 kg/m^3 and 200 kg/m^3 respectively. High performance concrete superplasticizer, Conplast SP430 was used to reduce water cement ratio for a required workability**.** Results are given below in Table 3.5.

Table 3.5 : Fresh properties of SCC (Kathirvel et al., 2010)

Mix ID	Slump flow (mm)	T50 cm (sec)	Vfunnel (sec)	V @ 5min (sec)	L box (H2/H1)	U box (mm)
CS	741	1.08	6.82	2.5	0.986	08
1L	748	1.02	6.78	2.34	0.994	05
2L	716	1.24	7.10	2.66	0.917	12
3L	695	1.43	8.64	3.52	0.849	18
1Q	720	1.41	7.38	3.29	0.884	17
2Q	698	1.67	7.65	3.45	0.852	22.5
3Q	672	1.86	11.41	4.62	0.811	27

Workability test results were found out as significant as per the recommendations given by EFNARC. While replacing cement by limestone powder by 10% the flow properties was high when compared to control SCC and also the passing ability and filling ability also increased. For 20% and 30% it was within the permissible limit recommended by EFNARC. But it was slightly decreased when compared to control SCC and 10% lime replacement. While replacing cement by 10% quarry dust the flow properties was high when compared to control SCC. For 20 and 30% the flow properties decreased when compared to 10% quarry replacement but satisfies the acceptable limits.

3.2 Hardened Concrete Properties

3.2.1 Compressive Strength

Uysal And Sumer (2011) studied compressive strength of self compacting concrete replacing portland cement with different mineral admixtures . They prepared sixteen series of mix proportions, of which one is control, and fifteen were prepared by replacing portland cement (specific surface area 399.6 m^2/kg) with fly ash (FA)(15%, 25% and 35%) (proportion used is 83, 138, 193 kg/m^3 respectively) granulated blast furnace slag (GBFS)(20%, 40% and 60%) (110, 220, 330 kg/m^3 respectively) limestone powder (LP)(10%, 20% and 30%) (55, 110 165 kg/m^3 respectively), basalt powder (BP)(10%, 20% and 30%) (55, 110, 165 kg/m^3 respectively) and marble powder (MP)(10%, 20% and 30%) (55, 110, 165 kg/m^3 respectively). After the preliminary investigations, the total powder content was fixed to 550 kg/m^3 and the water–powder ratio (w/p) was selected as 0.33. A new generation polycarboxylate based superplasticizer was employed. A natural river sand and crushed limestone with a maximum size of 16 mm was used as fine and coarse aggregates, respectively. The specific gravity and water absorption properties of river sand and crushed limestone are 2.59%, 1.44%, and 2.73%, 0.22%, respectively.

It can be seen from Table 3.6, the compressive strength values are in the range of 64.87–51.65 MPa at 7 days. At 28 days, GBFS20 specimen is the highest one (77.97 MPa) and LP30 is the lowest one (60.21 MPa) respectively. At the early stage, pozzolanic reactions of FA and GBFS were not sufficient to increase compressive strength. But at 28 days the slower pozzolanic reactions played a part in the GBSF mixture and it has the highest compressive strength results. In the case of FA and GBFS, filling of the voids between the larger cement particles, and increasing production of secondary hydrates by pozzolanic reactions with the lime resulting from the primary hydration enhances compressive strength.

Here the role of BP and LP are also better understood as it only acts like inert filler reducing the compressive strength of the BP and LP series. But, at early ages, MP series have showed significant performance. This is about the physical nature of better packing, by addition of MP leads the compressive strength due to the better dispersion and the denser matrix of cement grains. The addition of FA and GBFS to SCC mixtures had positively affected late age behaviour at 90 and 400 days. The compressive strength values were in the range of 89.08–72.42 MPa at 90 days and were in the range of 105.69–78.38 MPa, respectively at 400 days.

Table 3.6 : Compressive strength of SCC mixtures (Uysal And Sumer,2011)

Code	7 days	28 days	90 days	400 days
Control	64.9	75.9	85.0	100.5
FA15	62.0	74.2	87.0	102.0
FA25	61.4	73.4	86.3	105.7
FA35	55.1	67.5	79.4	92.2
GBFS20	62.3	77.9	87.9	101.8
GBFS40	63.4	74.8	89.1	96.8
GBFS60	58.1	71.6	80.7	85.5
LP10	60.4	69.3	80.2	86.0
LP20	57.4	65.2	74.2	78.6
LP30	54.8	60.2	67.2	72.4
BP10	62.9	72.1	83.3	89.5
BP20	59.7	65.9	77.3	81.9
BP30	51.7	62.2	72.4	78.4
MP10	63.9	76.3	86.3	97.6
MP20	64.0	77.5	82.2	96.8
MP30	59.4	70.8	80.6	93.4

Kou And Poon (2009) studied compressive strength of self compacting concrete using recycled fine and coarse aggregates. They prepared three series of SCC mixtures with different fine recycled aggregate contents and water-to-binder (W/B) ratios. Ordinary Portland cement and fly ash (FA) were used as the cementitious materials in the SCC mixtures. Two types of fly ash was used, the first one was a fine fly ash (f-FA) which complied with BS 3892 with most of the particles passing through the 45 µm sieve. The other one was the rejected fly ash (r-FA) with most of the particles >45 µm.

In Series I, five SCC mixtures were prepared and a W/B ratio of 0.53 was used for all the concrete mixtures. No f-FA was added. The fine recycled aggregates were used as 0, 25, 50, 75 and 100% by volume replacements of the river sand. In Series II, five SCC mixtures were prepared with a W/B ratio of 0.44. 70 kg/m^3 of f-FA was added to increase the cementitious materials content. Similarly, the fine recycled aggregates were also used as 0, 25, 50, 75 and 100% by volume replacements of the fine natural aggregates. In Series III mixtures, 100% fine recycled aggregates were used to replace river sand and three W/B ratios of 0.44, 0.40 and 0.35 were employed. In all the concrete mixtures, the cement and r-FA contents were kept constant at levels of 340 kg/m^3 and 200 kg/m^3 respectively.

It is evident in Table 3.7 that at early ages (1, 4 and 7-day) compressive strength was slightly decreased as the % replacement of sand by the fine recycled aggregates increased from 50 to 100%. At the late curing ages (28 and 90-day), the compressive strength of the RA-SCC mixtures in Series I prepared with 75% and 100% fine recycled aggregates was approximately 10% lower than that of the control-1. The compressive strength of Series II SCC mixes was higher than that of Series I SCC mixtures due to reduced W/B ratios. Table 3.7 indicates that the compressive strengths of the RA-SCC mixtures were higher than that of the control-2. This may be due to the presence of f-FA, and the pozzolanic reaction between Ca(OH)2 in the fine recycled aggregate and the fly ash forming additional C–S–H and enhancing strength. Compressive strength of Series III prepared by using 100% fine recycled aggregate as the fine aggregate increases as the W/B ratio decreased at all the test ages.

Table 3.7 : Compressive strength of RA-SCC mixtures in Series I, II and III (Kou And Poon ,2009)

Mix code	Recycled agg. Fine (%)	W/B	Compressive strength (MPa)				
			1-day	4-day	7-day	28 -day	90-day
Series I							
Control - 1	0	0.53	10.3	26.8	32.9	44.3	56.5
RF20	25	0.53	11.2	29.0	34.0	44.5	54.7
RF50	50	0.53	8.8	25.3	31.1	43.4	55.7
RF75	75	0.53	9.4	26.0	29.7	41.3	50.8
RF100	100	0.53	9.8	23.6	29.2	38.7	50.1
Series II							
Control - 2	0	0.44	11.1	30.3	36.8	53.7	78.9
RF25	25	0.44	13.8	38.3	43.9	64.3	82.6
RF50	50	0.44	17.5	38.4	42.1	62.3	81.4
RF75	75	0.44	13.8	32.3	40.9	56.3	75.3
RF100	100	0.44	15.1	29.2	38.3	53.2	71.7
Series III							
RF100A	100	0.44	15.1	29.2	38.3	53.2	71.7
RF100B	100	0.40	15.6	33.1	44.0	59.1	77.0
RF100C	100	0.35	16.6	39.8	43.8	64.2	81.8

Nanthagopalan et al. (2011) : The main objective of there study is to explore the possibility of using manufactured sand (Msand) in self compacting concrete. In recent years, Msand produced by crushing rock deposits is being identified as a suitable alternative source for river sand in concrete. In this process, an attempt was made to understand the influence of paste volume and w/p ratio (water to powder ratio) on the properties of self-compacting concrete (SCC) using Msand. The powder and aggregate combinations were optimized by using the particle packing approach, which involves the selection of combinations having maximum packing density. The chemical admixtures (superplasticisers, viscosity modifying agent) were optimised based on simple empirical tests. Fresh concrete tests such as slump flow, T_{500} and J-ring were performed on SCC; hardened concrete tests were limited to compressive strength. From the results, it was observed that relatively higher paste volume is essential to achieve the required flow for SCC using Msand, as compared to river sand. Low and medium strength (25–60 MPa) SCCs were achieved by using Msand based on the approach adopted in the study. Results showed that it is possible to successfully utilize manufactured sand in producing SCC.

Khatib (2005) reported that in addition to the coarse recycled aggregates, fine recycled aggregates (<5 mm) can also be used to replace natural fine aggregates in the production of concrete. He reported that when natural fine aggregates in concrete were replaced by 0%, 25%, 50%, 75% and 100% fine recycled aggregates and the free water/cement ratio was kept constant for all the mixes, the 28-day strength of the concrete developed at a slower rate. Furthermore, the concrete mixtures containing fine recycled aggregates had higher shrinkage than the natural aggregates concrete.

Siddique (2010) reported compressive strength of self compacting concrete using class F fly ash. Five concrete mixes were made, which had total powder content to 550 kg/m^3 (cement + fly ash). Proportions of cement are 465, 440, 415, 385 and 255 kg/m^3 respectively. Coarse aggregate content was maintained at 39% by volume (590 kg/m^3) of concrete and fine aggregate content at 45% by volume of mortar in concrete (910 kg/ m^3), the w/p ratio was kept at 0.41–0.44 by weight with air-content being assumed to be 2%. A polycarboxylic ether based superplasticizer complying with ASTM C 494 type F, with density approximately 1.10 and pH approximately 5.0 was used. The coarse and fine aggregates had a specific gravity of 2.67, and water absorptions of 0.95% and 0.90%, respectively. The mixes were prepared with five percentages of class F fly ash (15%; 85 kg/m^3, 20%; 110 kg/m^3, 25%; 135 kg/m^3, 30%; 165 kg/m^3 and 35%; 195 kg/m^3 respectively).

The compressive strength tests results of SCC mixes are given in Table 3.8 and shown in Fig. 3.4. 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 strength 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% (SCC5) to 15% (SCC1).

Table 3.8 : Compressive strength of SCC mixes. (Siddique ,2010)

Mix	Compressive Strength (MPa)			
	7 days	28 days	90 days	365days
SCC1	29.55	35.19	58.99	61.24
SCC2	27.99	33.15	52.86	54.60
SCC3	25.52	31.47	43.76	46.67
SCC4	23.98	30.66	41.96	44.87
SCC5	22.78	29.62	40.88	43.73

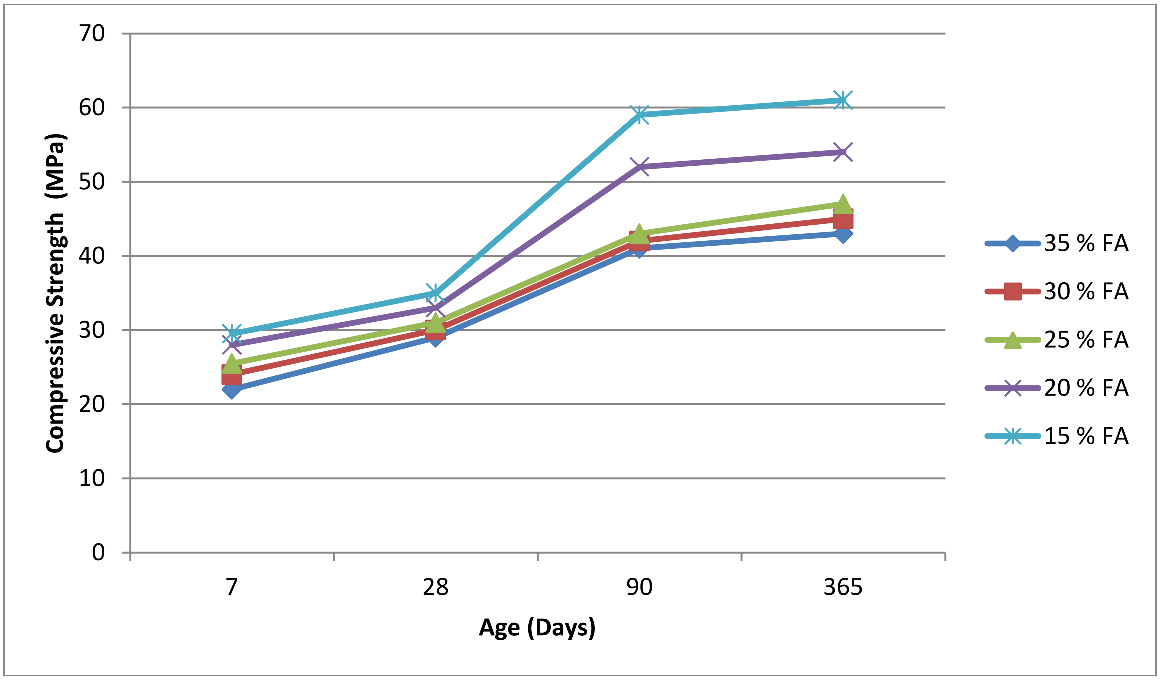

Fig. 3.4 : Compressive strength of SCC mixes at various ages. (Siddique ,2010)

Khaloo et al. (1999) investigated the influence of silica fume on compressive strength and durability of concrete. The percentage of silica fume was between 1% and 15% and the water-cement ratios ranged from 0.3 to 0.6. The coarse and fine aggregates consisted of river gravel and sand with maximum size of 25 mm and 5 mm, respectively. The test results indicated that 5 to 10 percent by mass replacement of silica fume for cement provided the highest strength for short and long terms. Compressive strength of silica fume concrete at 28 days compared to conventional concrete increased by 20 to 40 percent, for all the variables considered.

Grdic et al. (2010) gave compressive strength results conducted on self compacting concrete prepared by replacing coarse aggregates with recycled aggregates in different proportions . For making of concrete mixture the fractions of 0/4, 4/8 and 8/16 mm of the river aggregate were used, and the fractions 4/8 and 8/16 of recycled aggregate. They prepared three series of mix with 0%, 50% and 100% replacement of coarse aggregate with recycled aggregates respectively. Proportions used of recycled aggregates of fraction 4/8 and 8/16 was kept constant to 429 kg/m^3 in all three mixes. Limestone filler of specific gravity 2.692 g/cm^3 was used in proportion 260 kg/m^3 for all the mixes. Results of compressive strength test are shown below in Fig. 3.5.

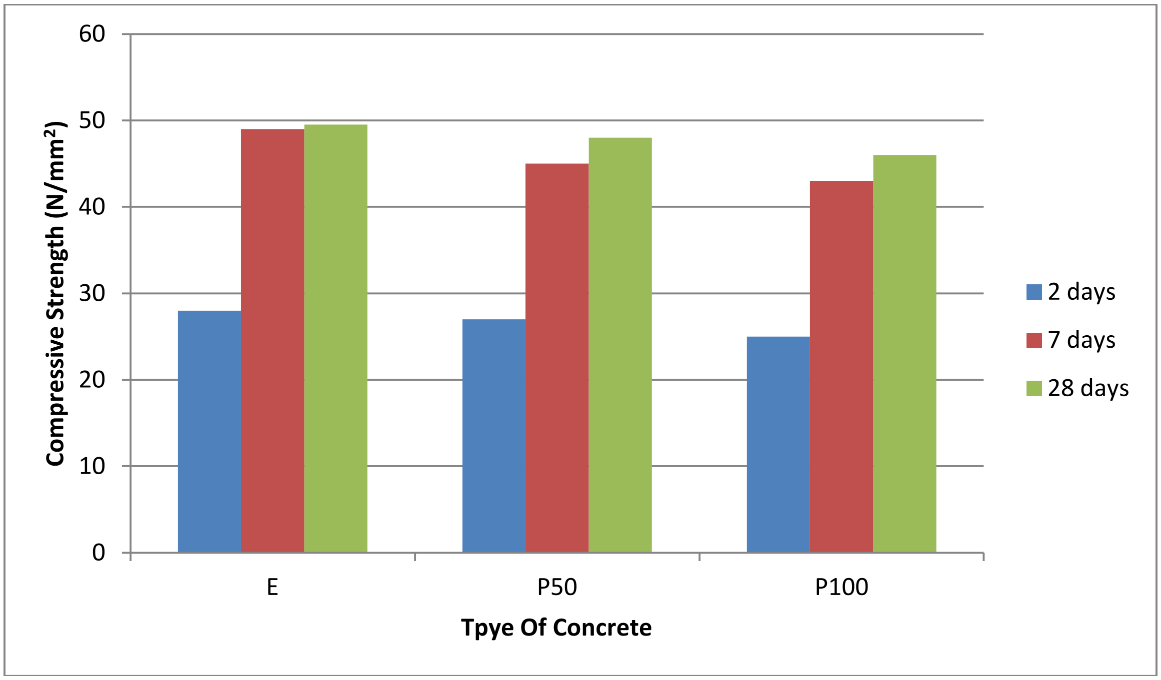

Fig. 3.5 : Graphic presentation of compressive strength test results (Grdic et al., 2010)

All three mixtures quickly gain early strength, and after 7 days they achieve more than 90% of the strength they have at the age of 28 days, which is the result of implementation of limestone filler. The explanation of the certain reduction of strength in those concretes with recycled aggregate lie in this aggregate's concrete microstructure. Namely, the main problem of application of recycled aggregate is its changeable and irregular and inconsistent quality, especially in the cases of the aggregate obtained by demolition of structural elements of a building.

Gesog˘lu et al. (2009) studied compressive strength of self compacting concrete incorporating fly ash, groung granulated blast furnance slag and silica fume. A total of 22 concrete mixtures were designed having a constant water/binder ratio of 0.44 and a total binder content of 450 kg/m^3. The control mixture included only a Portland cement (PC) as the binder while the remaining mixtures incorporated binary, ternary, and quaternary cementitious blends of PC, fly ash (FA), ground granulated blast furnace slag (S), and silica fume (SF). The replacement levels for both FA and S were 20%, 40% and 60% while those of SF were 5%, 10% and 15% by weight of cement. Proprtion of cement used ranges from 180 to 450 kg/m^3 for different mixtures. Proportions of fly ash, ground granulated blast furnace slag and silica fume are in range of 0 – 270 kg/m^3, 0 – 270 kg/m^3 and 0 – 67.5 kg/m^3 respectively.

Compressive strength of various concrete mixtures are given in Table 3.9. The compressive strength of SCCs was in the range of 42.5– 78.0 MPa. The binary use of PC + FA reduced compressive strength of SCCs with increasing the replacement level of FA. Replacing PC with 60% FA caused a reduction in the compressive strength of about 40%. However, this adverse effect of FA seemed to be remedied by the combined use of the mineral admixtures. Interestingly, the concrete containing 10% FA and 10% S achieved the highest compressive strength of all 22 mixtures. There was a gradual decrease in the compressive strength of the concretes having ternary and/or quaternary blends including FA. Therefore, the test results suggested that it was the FA among the mineral admixtures used that governed the reduction in the compressive strength of the SCCs.

Table 3.9 : Compressive strength results (Gesog˘lu et al., 2009)

Mix	Compressive strength (MPa)
Control - PC	73.6
20FA	68.0
40FA	60.3
60FA	42.5
20S	72.6
40S	74.9
60S	65.7
5SF	71.2
10SF	76.1
15SF	74.8
15FA5SF	67.2
30FA10SF	57.6
45FA15SF	44.9
15S5SF	68.0
30S10SF	68.2
45S15SF	70.7
10FA10S	78.0
20FA20S	69.2
30FA30S	60.6
7.5FA7.5S5SF	76.0
15FA15S10SF	66.8
22.5FA22.5S15SF	55.2

Naik And Singh (1997) conducted tests on concretes containg 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.

Gesogˇlu And Guneyisi (2011) studied compressive strength of self compacting rubberized concretes with and without fly ash. At a water–cementitious material (w/cm) ratio of 0.35, the self-compacting concretes (SCCs) were produced by replacing the fine aggregate with four designated crump rubber contents of 0%, 5%, 15%, and 25% by fine aggregate volume. Moreover, the SCCs with fly ash were produced by partial substitution of cement with fly ash at varying amounts of 20% to 60%. Fly ash used was class F fly ash (FA) as per ASTM C618 such that the total amount of SiO2, Al2O3, and Fe2O3 content was about 83%. Four different series of self-compacting rubberized concrete (SCRC) mixtures were designed with a constant water–cementitious material (w/cm) ratio of 0.35 and total cementitious materials content of 550 kg/m^3. The first group of mixtures was designed to have only portland cement as the binder (550 kg/m3). However, the second, the third, and the fourth series of the mixtures contained fly ash partially replaced with portland cement at 20% (110 kg/m^3), 40% (220 kg/m^3), and 60% (330 kg/m^3) levels by weight. Proportion of crump rubber lies in range 0 to 128.1 kg/m^3.

Compression test was conducted on the 150 mm cube specimens. The overall compressive strength ranged from 16.2 to 71.3 MPa and from 20.8 to 86.7 MPa at 28 and 90 days, respectively. It was evident that there was a marked reduction in the compressive strength of concretes with increasing rubber content, irrespective of the testing age.

Previous studies have shown that the use of mineral admixtures such as fly ash and blast furnace slag could increase the slump of the concrete mix without increasing its cost, while reducing the dosage of superplasticizer needed to obtain similar slump flow compared to concrete made with Portland cement only (Yahia et al.,1999). Also, the use of fly ash improves rheological properties and reduces the cracking potential of concrete as it lowers the heat of hydration of the cement (Kurita et al.,1998). Studies have shown that fly ash replacement up to 30% results in a significant improvement of the rheological properties of flowing concretes (Kim et al.,1996) .

3.2.2 Tensile Strength

Siddique (2010) studied tensile strength of self compacting concrete using class F fly ash. Five concrete mixes were made, which had total powder content to 550 kg/m^3 (cement + fly ash). The mixes were prepared with five percentages of class F fly ash (15%; 85 kg/m^3, 20%; 110 kg/m^3, 25%; 135 kg/m^3, 30%; 165 kg/m^3 and 35%; 195 kg/m^3 respectively). Proportions of cement are 465, 440, 415, 385 and 255 kg/m^3 respectively. Coarse aggregate content was maintained at 39% by volume (590 kg/m^3) of concrete and fine aggregate content at 45% by volume of mortar in concrete (910 kg/ m^3), the w/p ratio was kept at 0.41–0.44

Splitting tensile strength test results of SCC mixes are given in Table 3.10, and shown in Fig 3.6. SCC mixes achieved splitting tensile strength from 1.55 to 2.40, 1.76 to 2.68, and 2.12 to 2.96 MPa at 28, 90 and 365 days, with the increase in fly ash content from 15 to 35%. Splitting tensile strength increased with a decrease in the percentage of the fly ash and the water-to-cementitious materials ratio.

Table 3.10 : Splitting tensile strength of SCC mixes. (Siddique ,2010)

Mix	Splitting tensile strength		
	28 day	90 day	365 day
SCC1	2.40	2.68	2.96
SCC2	2.12	2.44	2.61
SCC3	1.83	2.12	2.33
SCC4	1.76	1.97	2.26
SCC5	1.55	1.76	2.12

With the increase in cement content, the strength of SCC1 (15% fly ash) gradually increased to 2.40 MPa at 28 days. An increase of about 54% of strength at 28 days and 40% at 365 days was observed with the decrease of the fly ash contents from 35% (SCC5) to 15% (SCC1). As the percentage of fly ash in mixes decreased, the tensile strength increased at all ages.

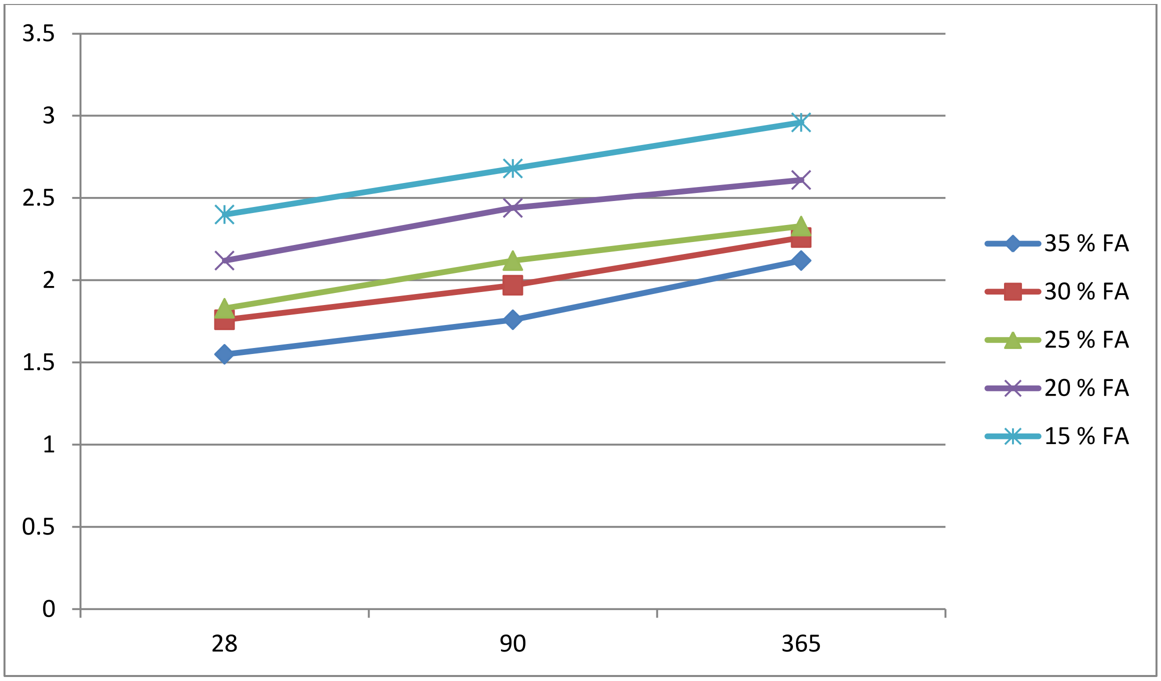

Fig. 3.6 : Splitting tensile strength of SCC mixes. (Siddique, 2010)

Kou And Poon (2009) reported tensile strength of self compacting concrete using recycled fine and coarse aggregates. They prepared three series of SCC mixtures with different fine recycled aggregate contents and water-to-binder (W/B) ratios. Ordinary Portland cement and fly ash (FA) were used as the cementitious materials in the SCC mixtures. Two types of fly ash was used, the first one was a fine fly ash (f-FA) which complied with BS 3892 with most of the particles passing through the 45 µm sieve. The other one was the rejected fly ash (r-FA) with most of the particles >45 µm.

In Series I, five SCC mixtures were prepared and a W/B ratio of 0.53 was used for all the concrete mixtures. No f-FA was added. The fine recycled aggregates were used as 0, 25, 50, 75 and 100% by volume replacements of the river sand. In Series II, five SCC mixtures were prepared with a W/B ratio of 0.44. 70 kg/m^3 of f-FA was added to increase the cementitious materials content. Similarly, the fine recycled aggregates were also used as 0, 25, 50, 75 and 100% by volume replacements of the fine natural aggregates. In Series III mixtures, 100% fine recycled aggregates were used to replace river sand and three W/B ratios of 0.44, 0.40 and 0.35 were employed. In all the concrete mixtures, the cement and r-FA contents were kept constant at levels of 340 kg/m^3 and 200 kg/m^3 respectively.

Splitting tensile strengths of concrete were measured using a Denison compression machine with a loading capacity of 3000 kN according to BS 1881 Part 116 and 117,respectively. The splitting tensile strength test was carried out on the concrete specimens at the age of 28 days. The results of the tensile splitting strength of the SCC mixtures in Series I, II and III at 28 days are shown Fig. 3.7. Each presented value is the average of three measurements. It can be seen that the 28-day tensile splitting strengths of the RA-SCC mixtures in Series I were slightly lower than that of the control-1 mixture. But the tensile splitting strengths of the Series II mixes were higher than that of the control-2, as was seen for compressive strengths.

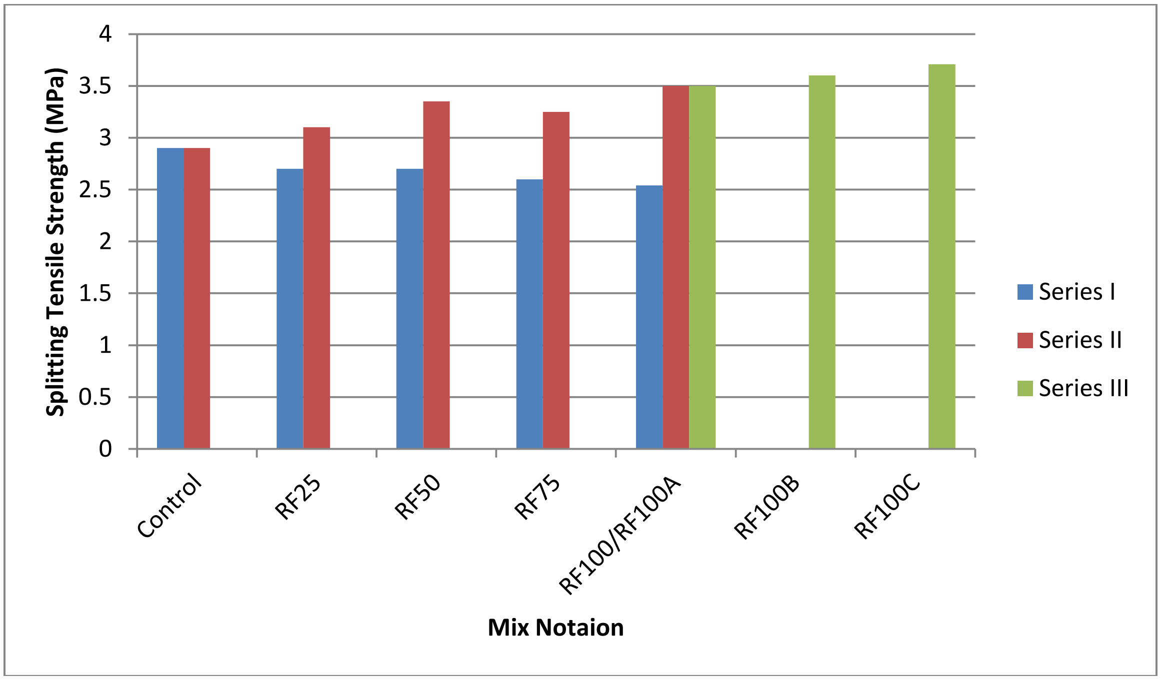

Fig. 3.7 : Splitting tensile strength of RA-SCC in Series I, II, and III at 28 days. (Kou And Poon, 2009)

Sahmaran et al. (2009) studied the tensile strength of self compacting concrete using fly ash. Spilt tensile strength tests were carried out at 28, 90 and 180 days respectively. The split tensile strength ranges from 3.21 to 5.07 MPa, 3.64 to 5.14 MPa and 4.19 to 5.64 MPa at 28, 90 and 180 days, respectively. The split tensile strength of all SCC mixtures increased with age. The results showed that, an increase in the FA content decreased the split tensile strength of the SCC especially at 28 days. SCC mixtures containing 30–50% FA replacement showed higher split tensile strength than SCC mixtures containing 60–70% FA replacement. The mixtures containing 60–70% FA showed lower tensile strength probably due to the weaker bond between the matrix and the aggregates.

Grdic et al. (2010) gave tensile strength results conducted on self compacting concrete prepared by replacing coarse aggregates with recycled aggregates in different proportions (0% , 50% and 100% replacement). For making of concrete mixture, the fractions of 0/4, 4/8 and 8/16 mm of the river aggregate were used, and the fractions 4/8 and 8/16 of recycled aggregate. They prepared three series of mix with 0%, 50% and 100% replacement of coarse aggregate with recycled aggregates respectively. Proportions used of recycled aggregates of fraction 4/8 and 8/16 was kept constant to 429 kg/m^3 in all three mixes. Limestone filler of specific gravity 2.692 g/cm^3 was used in proportion 260 kg/m^3 for all the mixes Results are shown below in Fig. 3.8. Results of the tensile strength testing by bending indicate that hardness of control concrete after 28 days is higher for 0.18 N/ mm^2 or 2.49% in respect to the concrete with 50% of coarse recycled aggregated and for 1.01 N/mm^2 or 13.95% in comparison to the concrete with 100% of coarse recycled aggregate. This reduction of strength was caused, by the changes in the concrete microstructure.

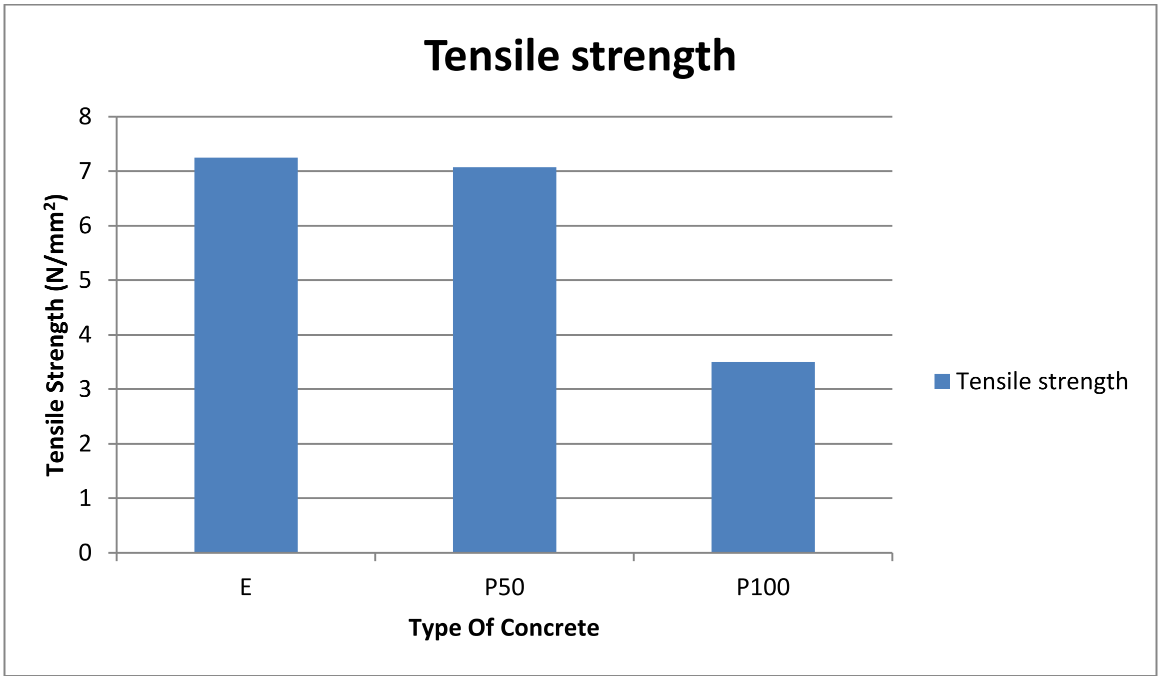

Fig. 3.8 : Tensile strength of SCC (Grdic et al., 2010)

Qian and Li (2001) investigated the tensile strength of concrete incorporating 0, 5, 10, and 15% metakaolin as partial replacement of cement. Metakaolin had specific surface area 12000 m^2/kg, and its average particle diameter was 2.23 μm. 300×100×20 mm samples were tested under direct tension. Tests were conducted at the age of 28 days. Tensile strength test results are presented in Table 3.11. The results showed that tensile strength of concrete increased systematically with increasing metakaolin replacement level. The average tensile strength increases were 7% (5% metakaolin), 16% (10% metakaolin), and 28% (15% metakaolin), and the average ultimate strain increases were 3%(5%metakaolin), 19%(10%metakaolin), and 27%

(15% metakaolin). The tensile elasticity modulus for these specimens is in the range from 26 to 27 GPa.

Table 3.11 : Tensile strength of SCC (Qian and Li ,2001)

Age (Days)	Tensile Strength (MPa)			
	MK (0%)	MK (5%)	MK (10%)	MK (15%)
28	3.35	3.58	3.88	4.29

Dehwah (2012) presents the results of a study conducted to evaluate the mechanical properties of self-compacting concrete (SCC) prepared using quarry dust powder (QDP), silica fume (SF) plus QDP or only fly ash (FA). Trials were conducted to assess the proportions of QDP, SF + QDP or FA required for producing SCC meeting the flow criteria. SCC specimens were prepared and tested for compressive strength, pulse velocity, split tensile strength and flexural strength. The results indicated that the mechanical properties of SCC incorporating QDP (8–10%) were equal to or better than those of SCC prepared with either SF plus QDP or FA alone. The use of QDP alone results in a significant cost saving in regions where SF and FA have to be imported from other countries.

3.3. Durabilty Properties

3.3.1 Sulphate Resistance:

Solution of sulphate can attack the hardened cement paste in the concrete causing deterioration. The precise chemical reaction will depend on the nature of the sulphate present and the type of cement. In some clay soils the ground water is solution of magnesium and calcium sulphates. These salts reacts with the $Ca(OH)_2$ and the calcium aluminate hydrate in the concrete to produce gypsum and calcium sulphoaluminate. These products have considerably have greater volume than the compounds they replace, leading to expansion and disruption of the concrete. Sea water and de-icing salt also contain appreciable concentarions of sulphates. The rate and extent of sulphate attack depend upon the ease with which sulphate ions are able to penetrate the concrete and upon the chemical resistance of cement paste.

There have been numerous field studies on the distress caused to concrete structures generated by sulphate attack . In particular, volume of cementitious paste (34–40%) and the larger powder content (400–600 kg/m3) of SCC can make it particularly vulnerable to chemical attack, for example by sulphate solutions. Since the last decade, SCC has been widely used in areas vulnerable to sulphate attack such as substructures, infrastructure and industrial floors. Sulphate attack has often been discussed in terms of the reaction between the hydrates in cement pastes and dissolved compounds, such as sodium sulphate or magnesium sulphate, in the attacking solution (Taylor 1997).

The classical form of sulphate attack involves alkali sulphates such as sodium sulphate which reacts with calcium hydroxide and calcium aluminate hydrate to form gypsum and ettringite. The gypsum and ettringite formed as a result of sulphate attack is significantly more voluminous (1.2–2.2 times) than the initial reactants, which can cause expansion, cracking, and deterioration of concrete by the reaction of SO_2_4 ions (Bonen, 1993). A magnesium sulphate solution may cause the deterioration of concrete due to the formation of Mg-containing hydrates (e.g. M–S–H gel), as well as gypsum and thaumasite. Some researchers have reported on the sulphate resistance imparted by mineral admixtures, which is generally incorporated in concrete to improve its engineering properties and durability.

Uysal And Sumer (2011) investigated effect of different mineral admixtures on the sulphate resisstance of self compacting concrete. They prepared sixteen series of mix proportions, of which one is control, and fifteen were prepared by replacing Portland cement with fly ash (FA)(15%, 25% and 35%) (proportion used is 83, 138, 193 kg/m^3 respectively) granulated blast furnace slag (GBFS)(20%, 40% and 60%) (110, 220, 330 kg/m^3 respectively) limestone powder (LP)(10%, 20% and 30%) (55, 110 165 kg/m^3 respectively), basalt powder (BP)(10%, 20% and 30%) (55, 110, 165 kg/m^3 respectively) and marble powder (MP)(10%, 20% and 30%) (55, 110, 165 kg/m^3 respectively). A natural river sand and crushed limestone with a maximum size of 16 mm was used as fine and coarse aggregates respectively. The total powder content was fixed to 550 kg/m^3 and the water–powder ratio (w/p) was selected as 0.33 Experimental results of sulphate resistance include reduction in compressive strength loss and visual examination which have been subjected to 10% sodium and 10% magnesium sulphate solutions for 400 days.

The deterioration of the SCC cube specimens was investigated by determining the compressive strength loss, which was calculated as follows:

Compressive strength loss (%)= [(A-B)/A]x100

Where,

A is the average compressive strength of SCC specimens cured in tap water (MPa) and,
B is the average compressive strength of SCC specimens immersed in test solutions (MPa) for the same period.

*Visual examination*_: It was observed (Fig. 3.9) that a small amount of spalling at edges and corners of the GBFS40 specimen which showed the best performance exposed to 10% magnesium sulphate solution for 400 days. A white substance was deposited on the face of the

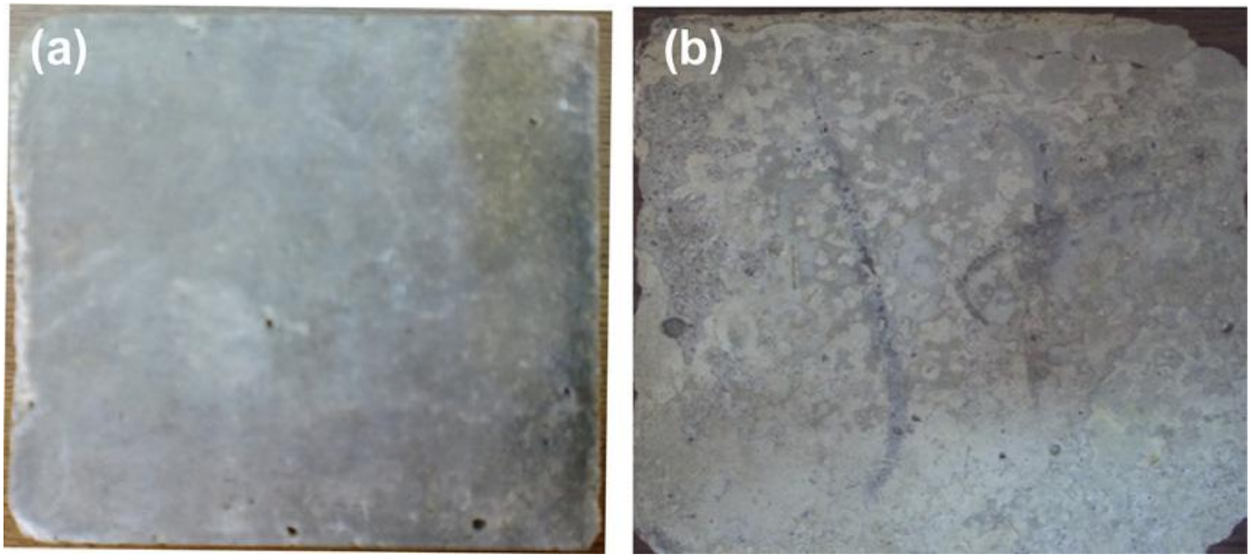

Fig. 3.9 : (a) The best case (GBFS40 specimen) and (b) the worst case (control specimen) of specimens in 10% magnesium sulphate solution after 400 days exposure. (Uysal And Sumer, 2011)

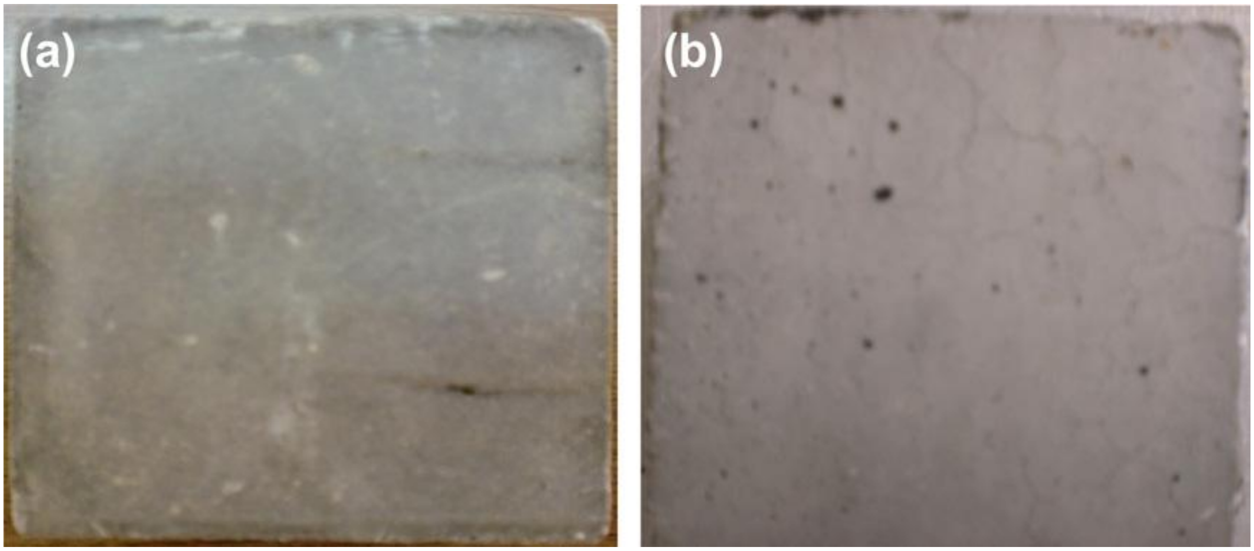

Fig. 3.10 : (a) The best case (GBFS40 specimen) and (b) the worst case (MP10 specimen) of specimens in 10% sodium sulphate solution after 400 days exposure. (Uysal And Sumer, 2011)

control specimen it was affected the worst in this solution exhibited relatively severe spalling at edges and corners.

After 400 days of immersion in sodium sulphate solution (Fig. 3.10), the visual examination of the GBFS40 specimen showed no visible deterioration with no detectable weight loss. Furthermore, the MP10 specimen exhibited visible deterioration spalling concrete especially at the corners and edges and some cracking.The visual examination of SCC specimens stored in the magnesium and sodium sulphate solutions for 400 days, indicated that the intensity of the damage by magnesium sulphate attack was greater than sodium sulphate attack.

Compressive strength loss : The evalution of the strength loss of SCC specimens placed in sodium sulphate and magnesium sulphate solutions is shown in Fig. 3.11 and 3.12, respectively. As can be seen from figures below , these strength results are discussed in terms of strength loss in order to highlight the damage caused to SCC mixtures by exposure to sulphate attack.

After 400 days exposure in the MgSO4 solution, the amounts of strength loss have been measured in the range of 4.55–13.09% for SCC mixtures. The strength loss decreased as the replacement of mineral admixtures increased. It is clear that the mixtures containing GBFS exhibited a much better resistance to magnesium sulphate attack than the mixtures containing other mineral admixtures. Moreover, these results indicate that the incorporation of mineral admixtures leads to reduced strength loss compared with those having only PC (control).

Similarly, GBFS series exihibit best resistance to sodium sulphate also. However, FA series performed very well resistance to sodium sulphate attack and showed lower strength loss than other series. The amounts of strength loss have been measured in the order of 1.52–9.68% for SCC mixtures, after 400 days exposure in the NaSO4 solution. Test results showed that the incorporation of mineral admixtures led to reduced strength loss compared with those having only PC (control) except MP10 specimen.

According to test results, control specimen had the highest strength loss among all the series in magnesium sulphate environments. The main reason of strength loss of control specimen that ettringite and gypsum formation caused spalling and cracking, while destruction of C–S–H caused softening and disintegration.

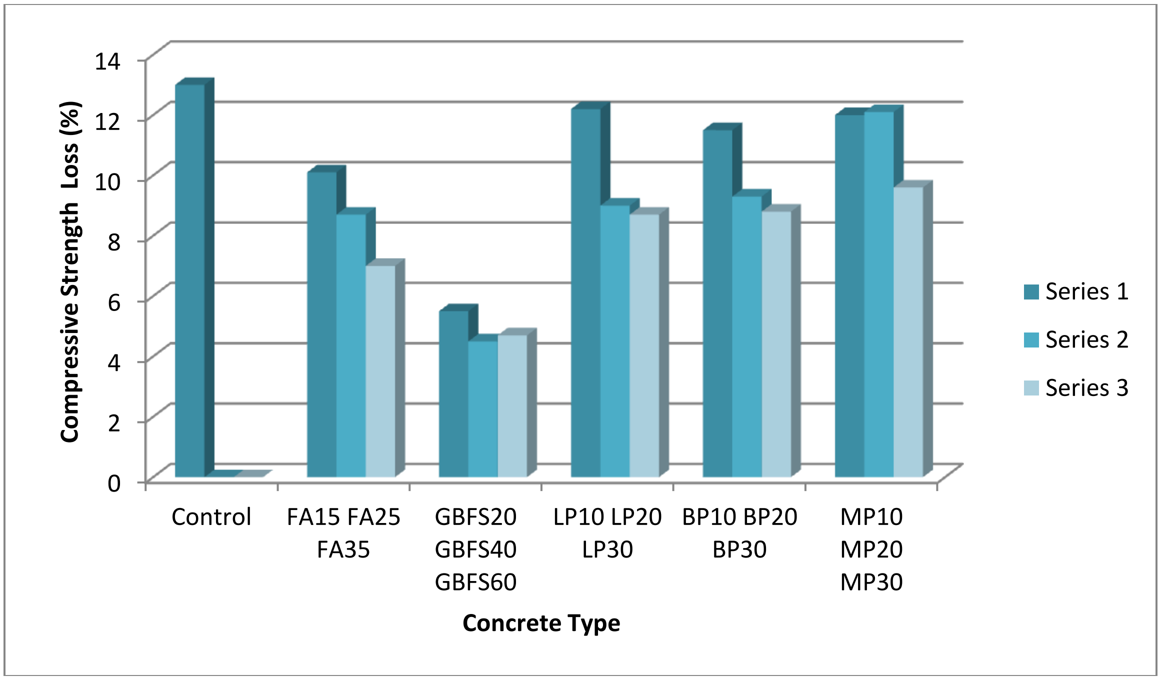

Fig. 3.11 : Compressive strength loss of SCC mixtures subjected to sulphate attack in 10% magnesium sulphate solution. (Uysal And Sumer, 2011)

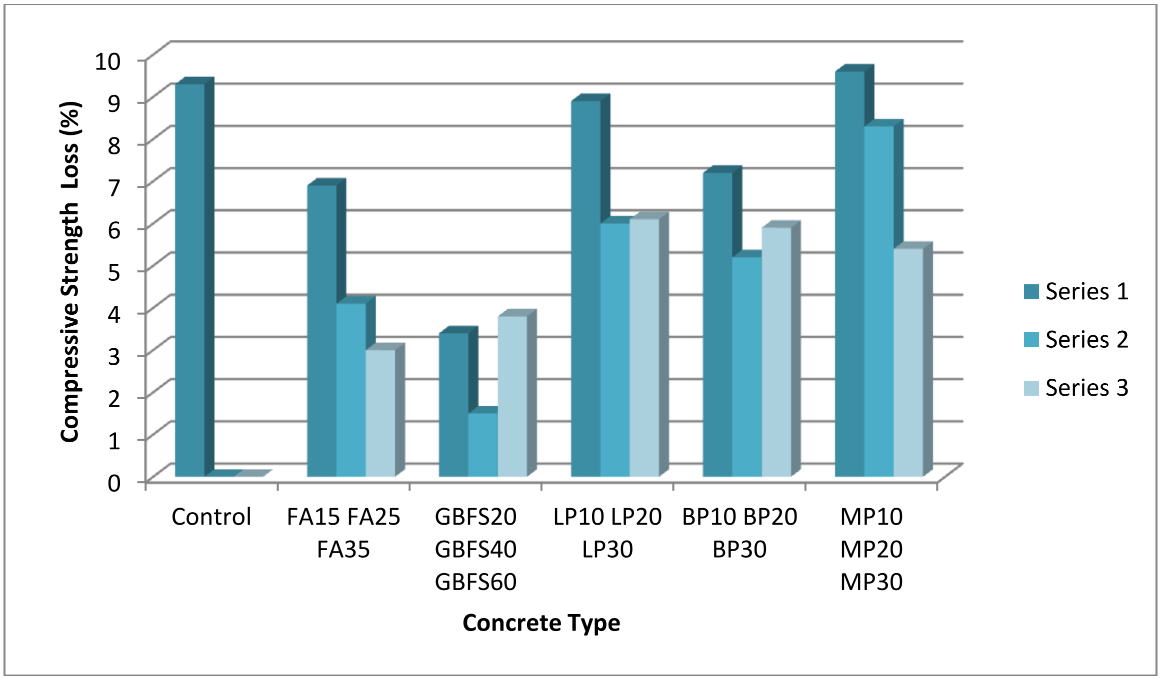

Fig. 3.12 : Compressive strength loss of SCC mixtures subjected to sulphate attack in 10% sodium sulphate solution. (Uysal And Sumer, 2011)

Kathirvel et al. (2010) Their investigation aims to study the durability of SCC with partial replacement of cement by Quarry and limestone (dust) powder. They replaced Ordinary portland cement (53 Grade) 10%, 20% and 30% by limestone powder and quarry dust respectively. Limestone powder with particle size less than 0.125 mm having a specific gravity of 2.53 was used. The specific gravity of crusher dust is 2.30. Mix proportions of cement and filler is 214.24 kg/m^3 and 200 kg/m^3 respectively. High performance concrete superplasticizer, Conplast SP430 was used to reduce water cement ratio for a required workability**.** Glenium Stream 2 is a viscosity modifying admixture which is used in combination with the Super Plasticizers in order to guarantee maximum efficiency. Ressistance to sulphate attack was measured in terms of decrease in compressive strength.

Fig. 3.13 and 3.14 shows the comparison of compressive strength of cubes (Quary Dust) placed in water and 5% of Sodium sulphate solution. At 90 days the compressive strength of control specimens, 1QD, 2QD, 3QD decreased by 1.7%, 1%, 1.7% and 2.3% respectively. For 120 days test results the decrease in compressive strength of control specimens, 1QD, 2QD, 3QD is by 2.2%, 2%, 2.3% and 2.5% respectively. Here the decrease in compressive strength of SCS and

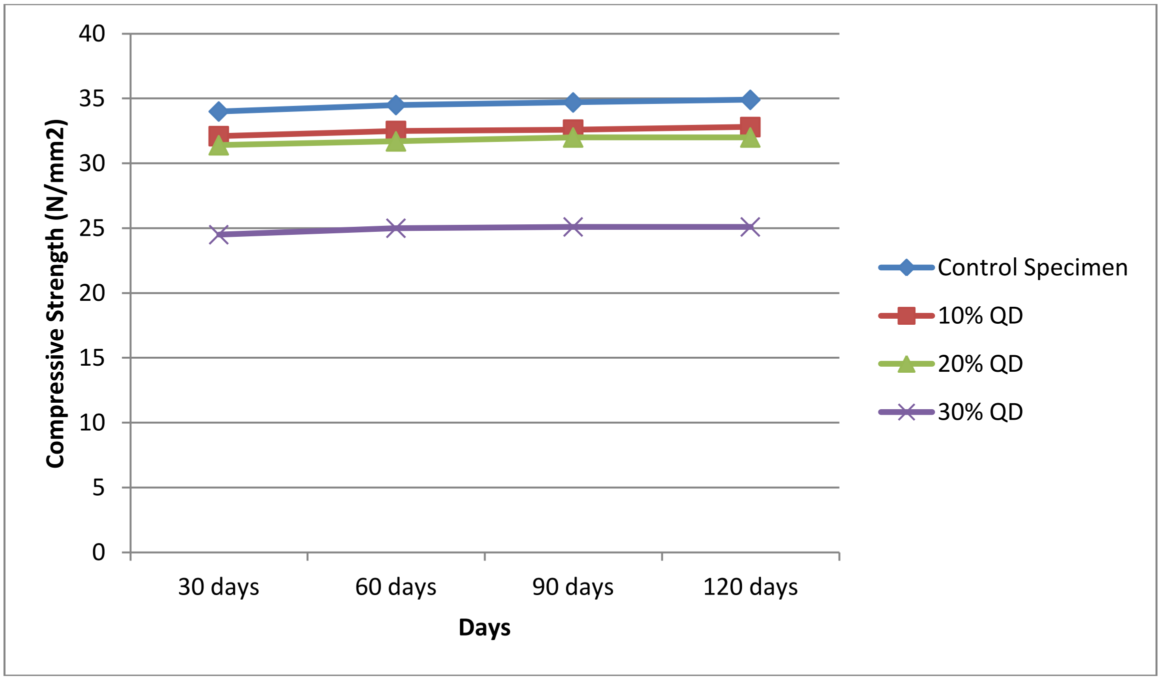

Fig. 3.13 : Compressive strength of cubes (QD) in water (Kathirvel et al.,2010)

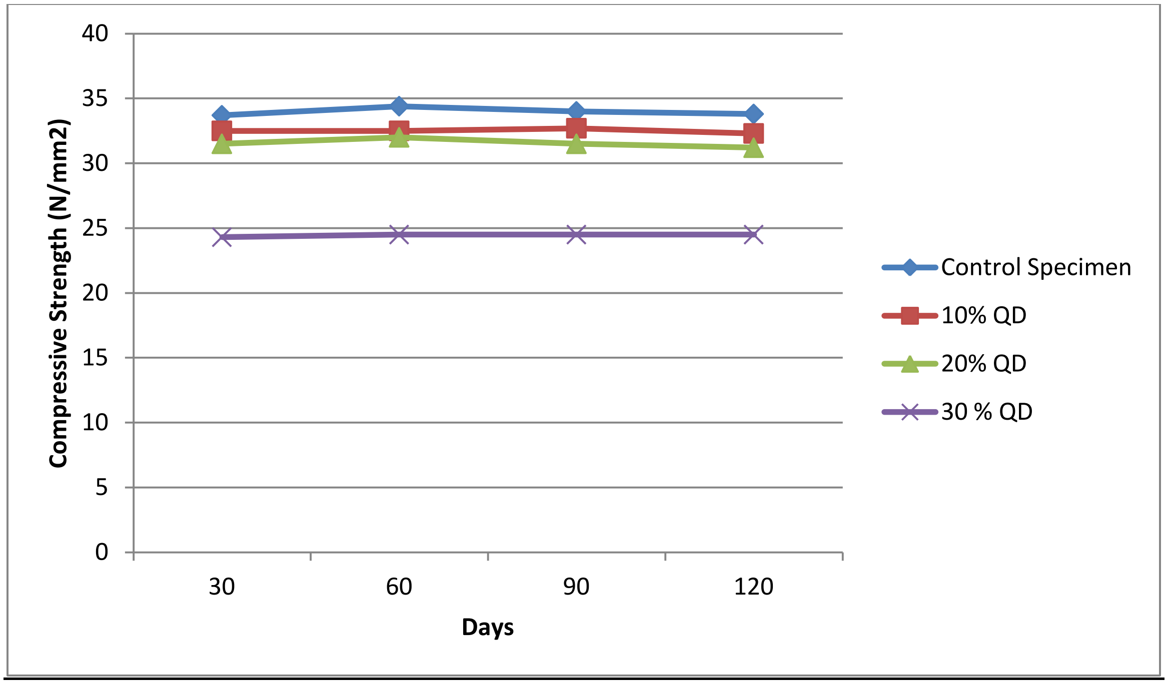

Fig. 3.14 : Compressive strength of cubes (QD) in sodium sulphate solution (Kathirvel et al., 2010)

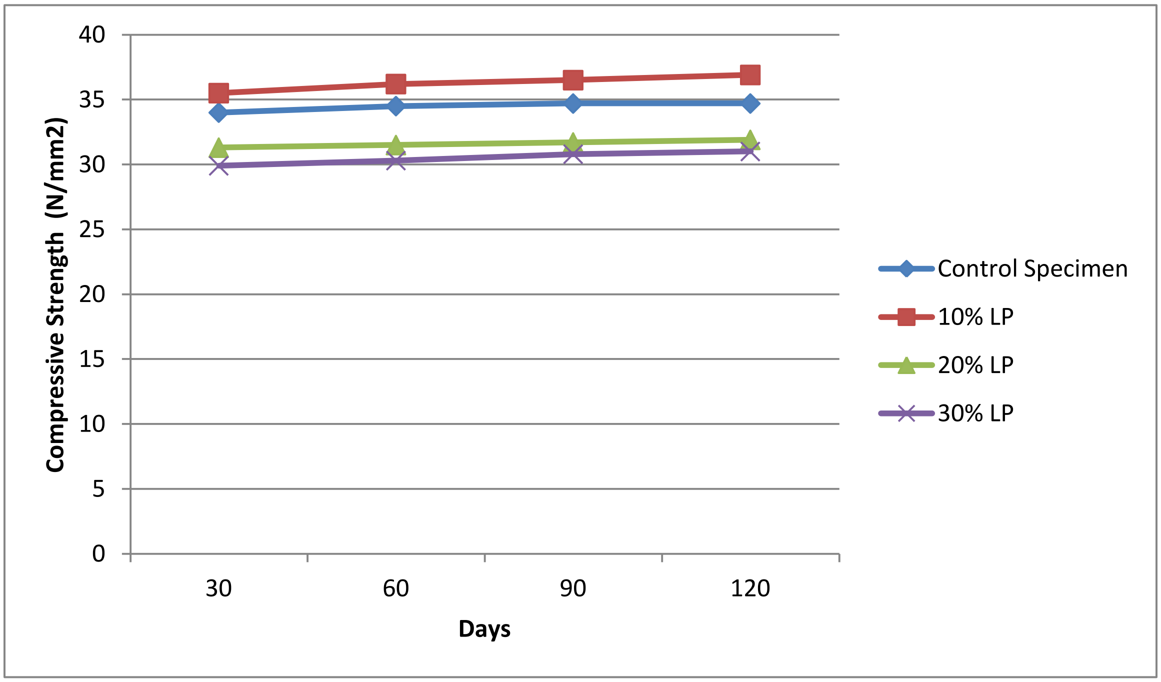

Fig. 3.15 : Compressive strength of cubes (LP) in water (Kathirvel et al., 2010)

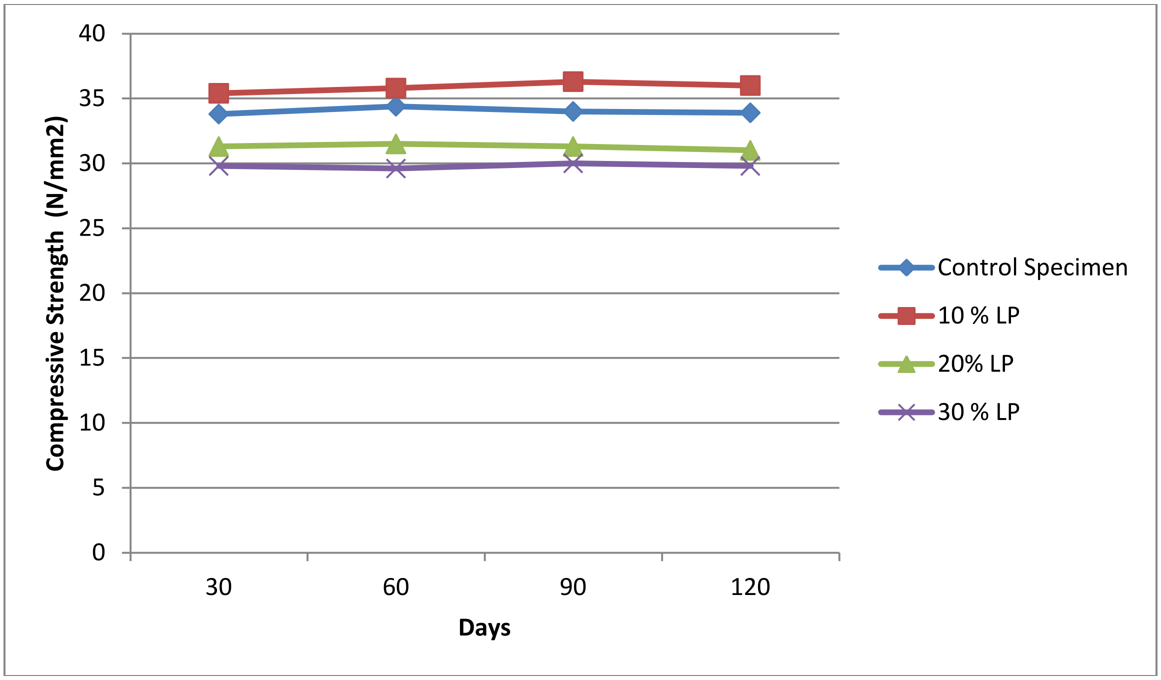

Fig. 3.16 : Compressive Strength of cubes (LP) sodium sulphate solution (Kathirvel et al., 2010)

3QD is high when compared to other specimens. The specimen 1QD shows good resistant to sulphate attack when compared to other specimens.

The compressive strength of the specimens, SCS, 1LP, 2LP and 3LP decreases by an average of 0.4%, 0.7% for 28 and 60 days respectively (Fig. 3.15 and 3.16). The decrease in compressive strength of the specimens SCS, 1LP, 2LP and 3LP at 90 days decreases by 1.7%, 0.6%, 1.3% and 2.7% respectively. By the 120 days results the SCS and 3LP specimen decreases by 2.2% and 3.5% respectively. The decrease in compressive strength is high when compared to 1LP and 2LP specimens. The compressive strength of the specimens 1LP shows slight decrease in strength by 1.5% showing good resistance to sulphate attack when compared to other specimens.

Bassuoni And Nehdi (2007) Self compacting concrete (SCC) is increasingly being used in numerous concrete applications some of which are vulnerable to sulfuric acid attack. The mixture design of SCC is different than that of normal concrete, and thus its long-term durability characteristics are still uncertain. Their study aims at investigating the resistance of a variable range of SCC mixture designs to sulfuric acid attack. The main test variables include the cementitious materials type (single, binary, ternary and quaternary binders), the sand-to-total aggregates mass ratio, and the inclusion of fibre reinforcement (single and hybrid). The investigation comprised two consecutive 6-week phases of immersion of test specimens in sulfuric acid solutions with a maximum pH threshold of 2.5 and 1.0, respectively. In total 24 SCC mixtures were tested. The study reveals that the rate of attack, as expressed by mass loss versus time, is controlled by different factors at each exposure phase. The advantages of blended binders and hybrid (steel + polypropylene) fibres in improving the resistance of SCC to sulfuric acid attack are highlighted.

Persson (2003) did a laboratory study on sulphate resistance of self-compacting concrete (SCC). For this purpose, more than 40 cylinders of concrete were subjected to a solution with sodium sulphate, sea or distilled water during 900 days. Age at start of testing was either 28 or 90 days. Weight and internal fundamental frequency (IFF) were measured. Comparison was done with the corresponding properties of vibrated concrete (VC). When cured in a solution with sodium sulphate, the results show larger loss of mass of SCC than that of VC probably due to the limestone filler content in SCC. After curing in water, sea or distilled, no such weight difference between the curing types was observe. IFF did not decrease or differ between the two types of concrete, i.e. no internal deterioration took place due to thaumasite sulphate attack (TSA) during the 900 days of exposure.

El-Dieb (2009) invesitigated effect of steel fibres in different volume fraction on durability of high strength self compacting concrete made of local available material. Durability of the concrete in high sulfate and high temperature condition (i.e. resembling Gulf environment) is evaluated. Test results indicate that local material can produce UHS–FRC. The ductility of the concrete is greatly improved by the incorporation of steel fibers and increases as the fiber volume increases. The inclusion of steel fibers did not have significant effect on the durability of the concrete in the sulfate environment. Microstructural investigations of UHS–FRC concrete were also performed.

4. Experimental Programmes

In the experimental program, the comparison of the properties of Self Compacting concrete made with and without silica fume and metakolin, used as supplementary cementing material is done. Discussion about the material used is done in this chapter. The basic tests carried out on concrete samples in plastic stage are also discussed in this chapter, followed by a brief description about mix deign and curing procedure adopted. Then the various tests conducted on the specimens are discussed.

4.1 Material used

In this section a brief discussion is done on the material used in this work. Various tests performed on this material are also discussed.

4.1.1 Cement

Cement is a fine, grey powder. The basic composition of cement is given below in Table 4.1. Cement 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..

Table 4.1 : Composition of Portland cement

Ingredient	% Content
CaO(Lime)	60-67
SiO_2 (Silica)	17-25
Al_2O_3(Alumina)	3-8
Fe_2O_3 (Iron Oxide)	0.5-6
MgO(Magnesia)	0.1-4
Alkalies	0.4-1.3
Sulphur	1-3

In this work J.K. cement of 43 grade was used for casting cubes and cylinders for all concrete mixes. The cement was of uniform color i.e. grey with a light greenish shade and was free from any hard lumps. The various tests conducted on cement are initial and final setting time, specific gravity, fineness and compressive strength. The results of above said tests are given below in Table 4.2 and 4.3.

Table 4.2 : Physical Properties of Cement

Test Conducted	Values Obtained	Standard values
Initial Setting time	42 min	Not < 30 minutes
Final Setting time	310 min	Not > 600 minutes
Fineness	4.9 %	<10
Specific gravity	3.09	-

Table 4.3 : Compressive strength of cement

Days	Specimen	Compressive Strength (N/mm^2)	Average Compressive Strength (N/mm^2)
7	1	35.2	35.3
	2	36.1	
	3	34.7	
28	1	42.8	44.1
	2	44.1	
	3	45.3	

It can be observed from tables that all the results satisfy the standard criteria.

4.1.2. Fine Aggregates

The sand used for the work was locally procured and conformed to Indian Standard Specifications IS: 383-1970. The sand was sieved through 4.75 mm sieve to remove any particles greater than 4.75 mm. The various other tests conducted are specific density, bulk density, fineness modulus, water absorption and sieve analysis. The results are given below in Table 4.4 and 4.5. The fine aggregated belonged to grading zone III.

Table 4.4 : Physical Properties of fine aggregates

Characteristics	Value
Specific gravity	2.51
Bulk density	1.3
Fineness modulus	2.62
Water absorption	0.89

Table 4.5 : Sieve analysis of fine aggregate

Sieve Size	Mass retained	Percentage Retained	Cumulative Percentage Retained	Percent Passing
4.75mm	5.0	0.5	0.5	99.5
2.36	78.0	7.80	8.30	91.7
1.18	185.0	18.5	26.80	73.2
600µm	227.0	22.7	49.50	50.5
300µm	281.0	28.1	77.6	22.4
150µm	223.8	22.38	99.98	0.20
2.50	0.20	0.20	∑=262.68	

Total weight taken = 1000gm

Fineness Modulus of sand = 2.62

4.1.3 Coarse Aggregates

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 this 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 4.6 and 4.7.

Table 4.6 : Physical Properties of Coarse Aggregates (10 mm)

Characteristics	**Value**
Type	Crushed
Specific Gravity	2.66
Total Water Absorption	0.56
Fineness Modulus	6.83

Table 4.7 : Sieve Analysis of Coarse Aggregates (10mm)

Sieve Size	**Mass Retained (gm)**	**Percentage Retained**	**Cumulative Percentage Retained**	**Percent Passing**
20 mm	0	0	0	100
10 mm	2516	83.89	83.87	16.13
4.75	474	15.8	99.67	0.33
PAN	10	0.33	∑= 183.54	

Total weight taken = 3Kg

FM of 10 mm Coarse aggregate = $\frac{183.54+500}{100}$ =6.83

4.1.4 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 unlesstests 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.

4.1.5 Silica Fume

Densified silica fume obtained from Mehtab Pvt. Limited is used in this work. It was grey in color. It is shown below in Fig. 4.1

Fig. 4.1 : Silica Fume mixed with cement

4.1.6. Metakolin

Metakolin used in this work was obtained from New delhi. It was white in color and is shown below in Fig. 4.2.

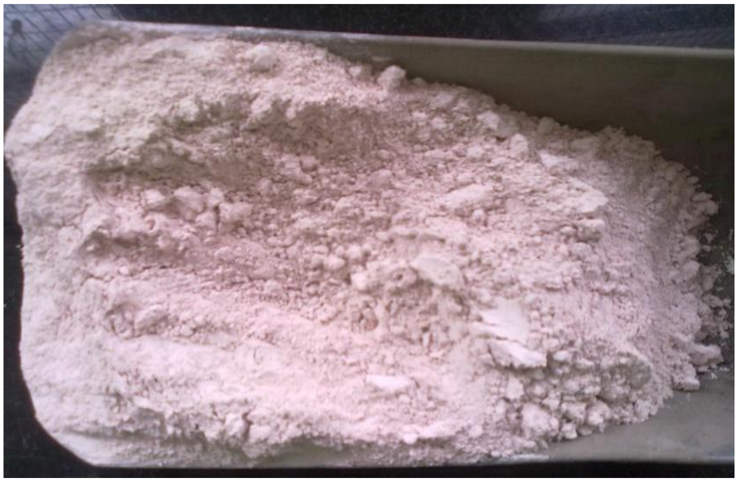

Fig. 4.2 : Metakolin

4.1.7. Admixture

Admixture used in this work is Conplast SP430, which complies with IS:9103:1979 and BS:5075 Part 3 and ASTM-C-494 type ‘F’ as a high range water reducing admixture. Conplast SP 430 is a ready to use admixture that is added to the concrete at the time of batching. Conplast SP430 is differentiated from conventional superplasticizers in that it is based on aqueous solution of lignosulphonates, organic polymer with long lateral chains. This greatly improves cement dispersion. Conplast SP430 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 is 1.22 to 1.225 at 30 degree C.

4.1.8. Magnasium Sulphate

Powder form of magnesium sulphate was obtained from Scientific Junction, Patiala. It was white in color. Its solution of strength 5% by adding it to water was made and used for sulphate resistance test.

Fig. 4.3 : Magnasium Sulphate

4.2 Casting

Before casting, the entire test specimen were cleaned and oiled properly. These were securely tightened to correct dimensions before casting. Care was taken that there is no gaps left from where there is any possibility of leakage of slurry. The coarse aggregates and fine aggregates were weighed first with accuracy. The concrete mixture was prepared by hand mixing on a non-absorbing platform. On the non-absorbing platform, the coarse and fine aggregates were mixed thoroughly. To this mixture, the cement was added. These were mixed to uniform color. Then 70 to 80 % water was added by making space in the center and rest was sprinkled on the mix. For each mix 27 samples were casted, 18 cubes (150 x 150 x 150mm), 9 cubes for compressive strength at 7, 28 and 56 days while 9 cubes for sulphate resistance and 9 cylinders for splitting tensile strength at 7, 28 and 56 days.

4.3 Mix Design

The mix designs are given below in Table 4.8.

Table 4.8 : Mix proportions

Mixture ID	**Cement kg/m^3**	**MK kg/m^3**	**SF Kg/m^3**	**MK (%)**	**SF (%)**	**Sand kg/m^3**	**C.A kg/m^3**	**Water (kg/m^3)**	**w/p**	**SP (kg/m^3)**	**SP (%)**
CM	550	0	0	0	0	910	590	265	.48	9.91	1.80
5%SF	522	-	28	-	5	910	590	265	.48	9.91	1.80
10%SF	495	-	55	-	10	910	590	265	.48	9.91	1.80
15%SF	467	-	83	-	15	910	590	265	.48	9.91	1.80
5%MK	522	28	-	5	-	910	590	265	.48	9.91	1.80
10%MK	495	55	-	10	-	910	590	265	.48	9.91	1.80
15%MK	467	83	-	15	-	910	590	265	.48	9.91	1.80

Where,

MK : Metakolin,

SF : Silica Fume,

CA : Coarse Aggregates,

CM : Control Mix,

SP : Conplast SP 430

4.4 Tests Conducted

4.4.1. Fresh Concrete Tests

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.

The various tests performed on fresh concrete to evaluate above given properties in this work are described below.

4.4.1.1. L- Box Test Method

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 below in Fig. 4.4.

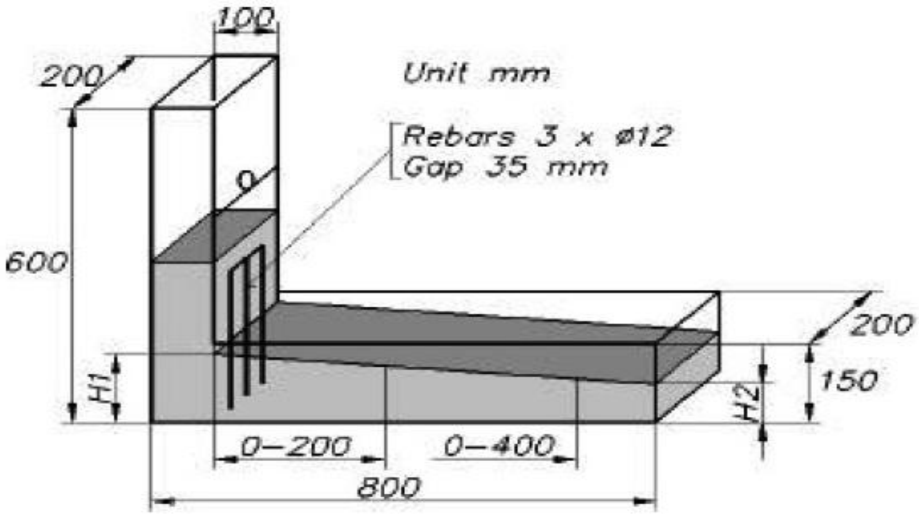

Fig. 4.4 : L box. (EFNARC, 2002).

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). 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.

Equipments

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

Procedure

- About 14 litre of concrete is needed to perform the test.
- Set the apparatus level on firm ground, ensure that the sliding gate can open freely and then close it.
- 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.

Results

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. T20 and T40 times can give some indication of ease of flow, but no suitable values have been generally agreed.

4.4.1.2 V – Funnel Test

The test is designed to measure flow ability of fresh concrete. The equipment consists of a V-shaped funnel, shown in Fig. 4.5 The funnel is filled with about 12 litres of concrete and the time taken for it to flow through the apparatus measured

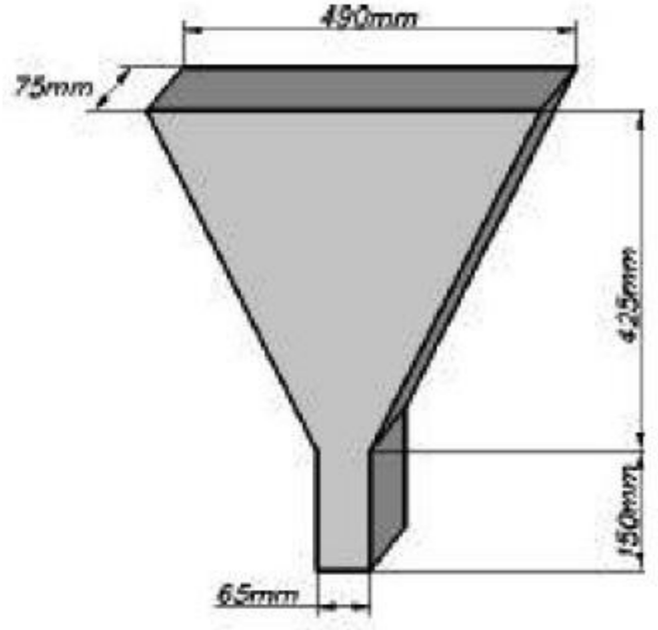

Fig. 4.5 : V- Funnel equipment. (EFNARC, 2002).

Equipments

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

Procedure

- 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.
- 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.

Results

This test measures the ease of flow of the concrete; shorter flow times indicate greater flow ability. 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.

4.4.1.3 Slump Flow Test

It is the most commonly used test and is used to assess the horizontal free flow of SCC in the absence of obstructions. 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. 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. Its equipment is shown below in Fig. 4.6. 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.

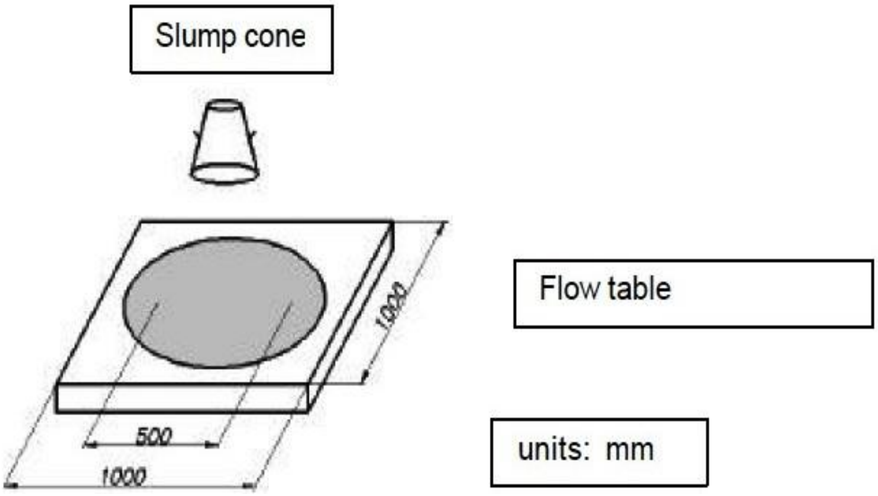

Fig. 4.6 : Slump flow test equipment. (EFNARC, 2002).

Equipment

- 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.
- 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 T_{50} 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).

Results

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 T_{50} time is a secondary indication of flow. A lower time indicates greater flow-ability.

4.4.1.4. U – Box 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. 4.7. 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.

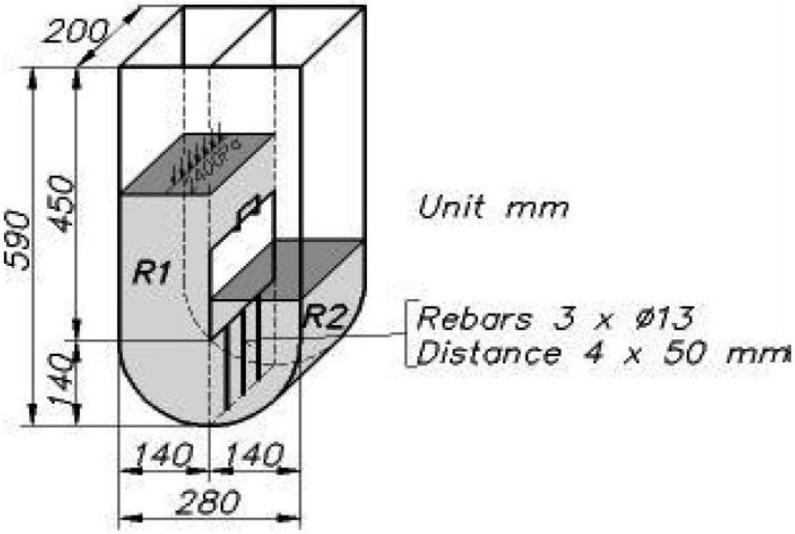

Fig. 4.7 : U box. (EFNARC, 2002)

Equipment

- U box of a stiff non absorbing material see figure 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.

Results

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

4.4.2. Hardend Concrete Tests

4.4.2.1 Compressive Strength Test (IS: 516 – 1959)

This test is performed on cube specimens to determine compressive strength at various ages.

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 rate specified. The permissible error shall be not 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 (preferably the one that normally will bear on the upper surface of the specimen) shall be fitted with a ball seating in the form of a portion of a 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 large as, and preferably larger than the nominal size of the specimen to which the load is applied.

Age at Test

Tests shall be made at recognized ages of the test specimens, the most usual being 7 and 28 days. Test at age of 56 days can also be performed. Ages of 13 weeks and one year are recommended if tests at greater ages are required. Where it may be necessary to obtain the early strengths, tests may be made at the ages of 24 hours ± ½ hour and 72 hours ± 2 hours. The ages shall be calculated from the time of the addition of water to the dry ingredients.

Number of Specimens

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

4.4.2.2 Splitting Tensile Strength Test (ASTM C496)

This test is performed on cylinder specimen to evaluate its tensile strength at various different ages.

Apparatus

Compression Testing Machine

Bearing Strips - 2 each, 1/8 in. thick plywood strips, 1 in. wide (the length shall be slightly longer that of the specimens). The bearing strips are placed between the specimen and the upper and lower bearing blocks of the testing machine (or between the specimen and supplementary bearing bars if used).

Supplementary Bearing Bars - Steel bar 2 in. wide, 3 in. thick, and 12 in. long.

Procedure

1) Draw diametric lines on each end of the specimen so that they are in the same axial plane.
2) Centre one of the plywood strips along the centre of the lower bearing block.

3) Place the specimen on the plywood strip and align so that the lines marked on the ends are vertical and centered over the plywood strip.
4) Place the second plywood strip and the bearing bar so that they are lengthwise on the cylinder, centered on the previously marked lines on the ends.
5) Apply the load continuously at a constant rate of 100 to 200 psi/minute of splitting tensile stress until failure occurs (the load rate is 11000 to 22000 lb/minute for 6”diameter by 12” long specimens).
6) Record the maximum load at failure.
7) Calculate the splitting tensile strength as follows:

$$f_{st}^{'} = \frac{2P}{\pi \ ld}$$

Where P is the maximum load at failure in pounds, and l and d are the length and diameter of the cylindrical specimen, respectively, in inches.

Report

1) Report the type of concrete, unit weight, and unconfined compressive strength.
2) Report the splitting tensile strength to the nearest 5 psi.

4.4.2.3. Sulphate Resistance Test

Tests performed for sulphate resistance in this work are compressive strength test after immersing the cube specimen in 5% magnesium sulphate solution for 7, 28 and 56 days. Before immersing them in sulphate solution, specimens are cured for 28 days in water under normal temperature. Compressive strength test has been already discussed above in article 4.4.2.1.

5. Result And Discussion

Here the results of the control concrete and concrete made with replacement of silica fume and metakolin with cement are discussed. The parameters such as Compressive strength, Splitting Tensile Strength, Sulphate Resistance are discussed and comparisons between the various mixes are represented.

5.1 Silica Fume

In this article effects of replacement of silica fume with cement on concrete are discussed. The extreme fineness and very high amorphous silicon dioxide content makes silica fume 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.

5.1.1 Fresh Concrete Properties

To study the effect of replacement of cement by silica fume in different proportions on fresh concrete properties, the SCC containing different proportion of silica fume were tested for Slump flow, V-funnel, U-Box, and L-box.

The results of fresh properties of all Self-compacting silica fume concretes are included in Table 5.1. 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.

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 8–11 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.

Table 5.1 : Fresh Concrete Properties (Silica fume)

Mixture ID	**Slump (mm)**	**V-funnel (seconds)**	**L-Box (H2/H1)**	**U-box(H1-H2)**
CM	585	11	0.9	34
5% SF	610	11	0.9	34
10% SF	660	10	0.9	40
15% SF	685	8	0.9	35

Fig. 5.1 : Slump Flow Test

Fig. 5.2 : V Funnel Test

5.1.2 Compressive Strength Test

To study the effect of replacement of silica fume in different proportions with cement on compressive strength, cube specimens of dimensions 150 x 150 x 150 mm are prepared. The replacement level of silica fume is 5%, 10% and 15%. Specimens are cured in water and tested at ages of 7, 28 and 56 days. Test results are given below in Table 5.2 and are represented in Fig. 5.3 and 5.4.

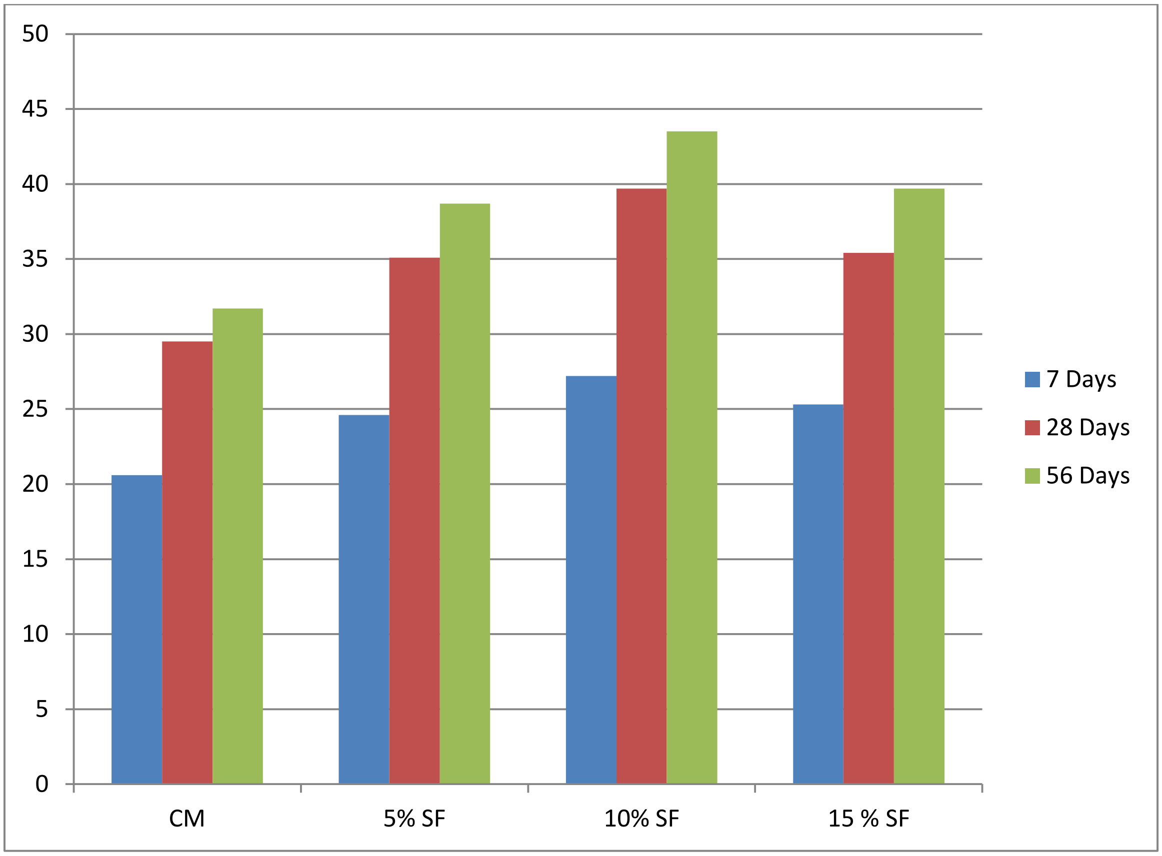

Fig. 5.3 : Compressive strength of SCC mixes with Silica fume

Table 5.2 : Compressive strength of SCC mixes with Silica fume

MIX	**Compressive Strength (N/mm^2)**			**Average Compressive Strength (N/mm^2)**		
	7 days	28 days	56 days	7 days	28 days	56 days
CM	20.7	28.4	31.7	20.6	29.5	31.7
	21.5	30.3	30.9			
	19.6	29.9	32.3			
5% SF	24.9	35.3	39.7	24.6	35.1	38.7
	25.7	34.1	38.9			
	24.4	35.9	37.5			
10% SF	28.1	39.6	44.2	27.2	39.7	43.5
	26.2	40.3	42.8			
	27.4	39.2	43.4			
15% SF	25.1	35.4	40.1	25.3	35.4	39.3
	24.1	36.1	38.8			
	26.8	34.9	39.0			
	21.5	30.3	30.9			

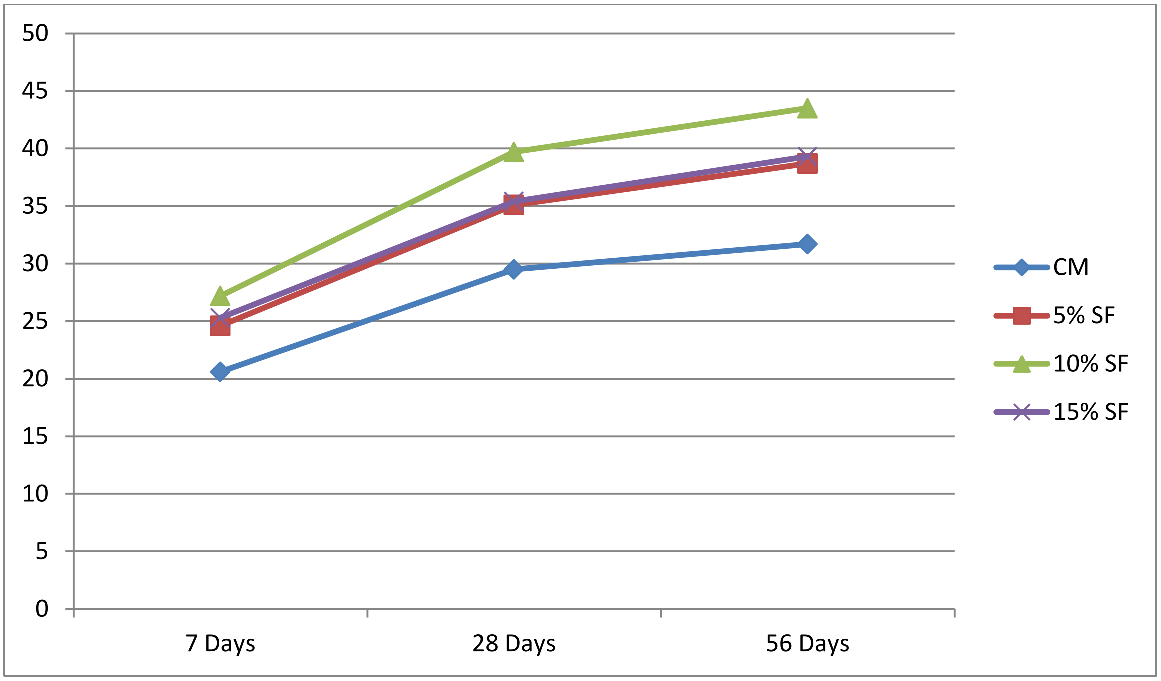

Fig 5.4 : Compressive Strength of SCC mixes

Fig. 5.5 : Compressive strength test in progress

The water-cement was kept constant at 0.48. The test results indicated that, when 5 to 10 percent by weight replacement of silica fume for cement is done, compressive strength increases. When 15% replacement of cement is done by silica fume, strength starts decreasing. Compressive strength of silica fume concrete at 28 days compared to control mix was increased by 18 to 35 percent with silica fume is added 5 to 10% respectively. While there is 20% increase in 28 days strength with 15 % replacement when compared to control specimen but there is decrease of compressive strength when compared to 10% replacement level.

Khaloo et al. (1999) investigated the influence of silica fume on compressive strength and durability of concrete. The percentage of silica fume was between 1% and 15% and the water-cement ratios ranged from 0.3 to 0.6. The coarse and fine aggregates consisted of river gravel and sand with maximum size of 25 mm and 5 mm, respectively. The test results indicated that 5 to 10 percent by mass replacement of silica fume for cement provided the highest strength for short and long terms. Compressive strength of silica fume concrete at 28 days compared to conventional concrete increased by 20 to 40 percent, for all the variables considered.

5.1.3 Splitting Tensile Strength Test

Split tensile strength studies were carried out at the age of 7, 28 and 56 days. Test results are given below in Table 5.3.

As seen in table, test results indicated that 5 to 10 percent by weight replacement of cement by silica fumet enhances strength for short and long terms. When we increase the replacement of silica fume at 15% strength goes on decreasing. There is increase of 20 to 40% splitting tensile strength of 5% and 10% silica fume concrete respectively, when compared to control mix at age of 28 days.

These results are represented graphically below in Fig. 5.6 and 5.7.

Table 5.3 : Splitting tensile strength of SCC mixes with Silica fume

MIX	**Splitting Tensile Strength (N/mm^2)**			**Average Splitting Tensile Strength (N/mm^2)**		
	7 days	28 days	56 days	7 days	28 days	56 days
CM	1.4	1.9	2.1	1.4	2.0	2.2
	1.3	2.1	2.0			
	1.5	2.0	2.2			
5% SF	1.8	2.5	2.9	1.7	2.5	2.8
	1.7	2.65	2.8			
	1.6	2.45	2.7			
10% SF	2.0	2.85	3.2	2.0	2.75	3.0
	1.85	2.75	2.8			
	2.1	2.65	3.0			
15% SF	1.7	2.7	2.8	1.6	2.55	2.9
	1.6	2.6	3.0			
	1.5	2.4	2.9			

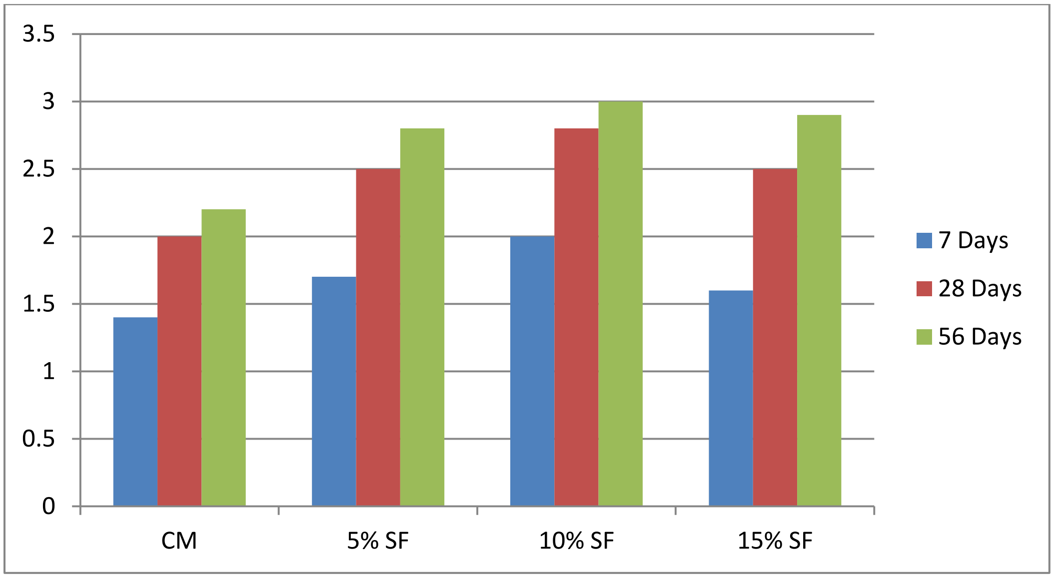

Fig. 5.6 : Splitting tensile strength of Silica Fume Concrete

Fig. 5.7 : Splitting tensile strength test

5.1.4 Resistance to sulphate attack of concrete

This test was conducted on 150 x 150 x 150mm cube specimens. The cubes were casted and cured in water for 28 days. Magnesium sulphate solution of strength 5% is used to evaluate sulphate resistance of concrete. Cubes are immersed in solution after 28 days curing, and are tested for compressive strength at 7, 28 and 56 days. Test results are given below in Table 5.4. There was decrease in compressive strength of specimens when compared with their normal compressive strengths. But when silica fume and metakolin are used as partial replacements of cement, then this strength loss is minimized.

When this compressive strength is compared with compressive strength of specimens cured in water at same ages, it is found that there is loss of compressive strength. After immersion in solution for 28 days, there is 1.5% loss of strength for control specimen. Control specimen simply cured in water has 56 day strength of 31.7 N/mm^2 while those immersed in solution have strength of 31.2 N/mm^2. When cement is replaced by silica fume, this loss tends to decrease. 10% replacement level gives the best result. There is loss of .7% strength. While there is loss of 1.0% and .8% respectively at replacement level of 5% and 15 %

Fig. 5.8 : Cube specimen placed in 5% $MgSo_4$ solution (After 28 days initial curing)

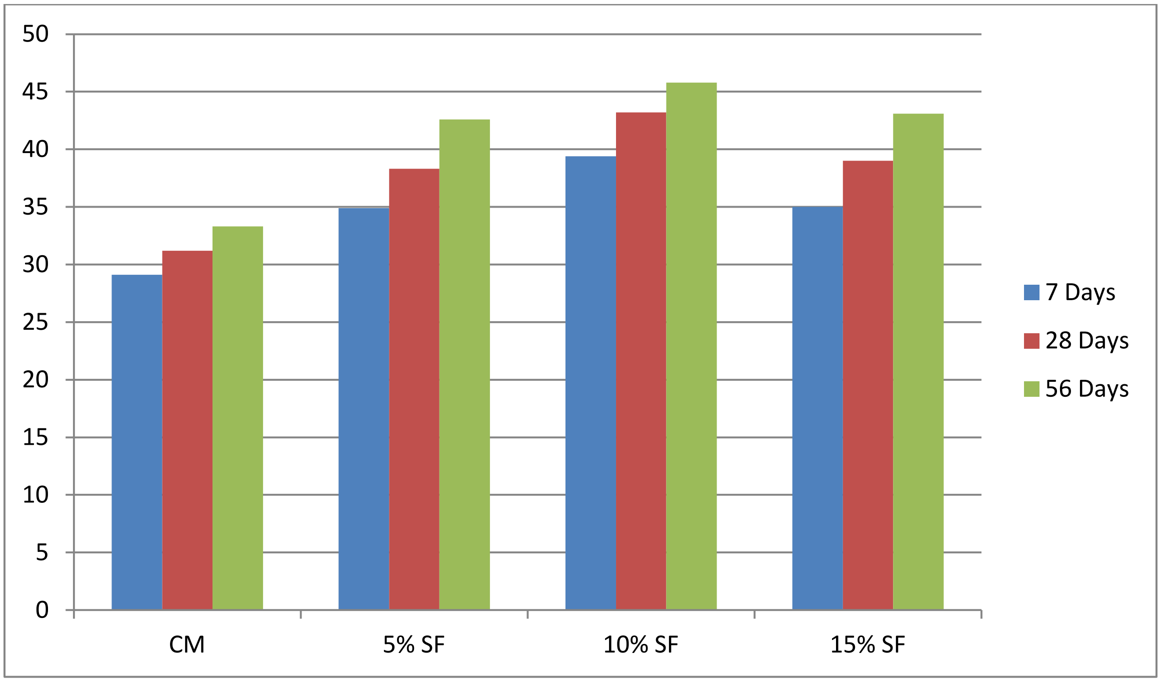

Fig. 5.9 : Compressive strength of silica fume concrete after immersion in 5% $MgSo_4$ solution (After 28 days initial curing)

Table 5.4 : Compressive strength of SCC mixes after immersion in MgSo$_4$ solution

MIX	**Compressive Strength (N/mm^2)(After 28 days curing)**			**Average Compressive Strength (N/mm^2)(After 28 days curing)**		
	7 days	28 days	56 days	7 days	28 days	56 days
CM	29.6	32.3	33.6	29.1	31.2	33.3
	29.1	30.4	32.5			
	28.5	31.0	33.9			
5% SF	35.5	38.0	42.1	34.9	38.3	42.6
	34.8	39.3	43.3			
	34.3	37.6	42.7			
10% SF	39.6	43.1	46.6	39.4	43.2	45.8
	38.2	42.7	44.8			
	39.4	43.8	46.0			
15% SF	35.3	39.0	42.6	35.0	39.0	43.1
	35.7	38.7	43.8			
	34.2	39.4	43.0			

These results are represented graphically above in Fig. 5.9. While loss in strength results are represented below in Fig. 5.10.

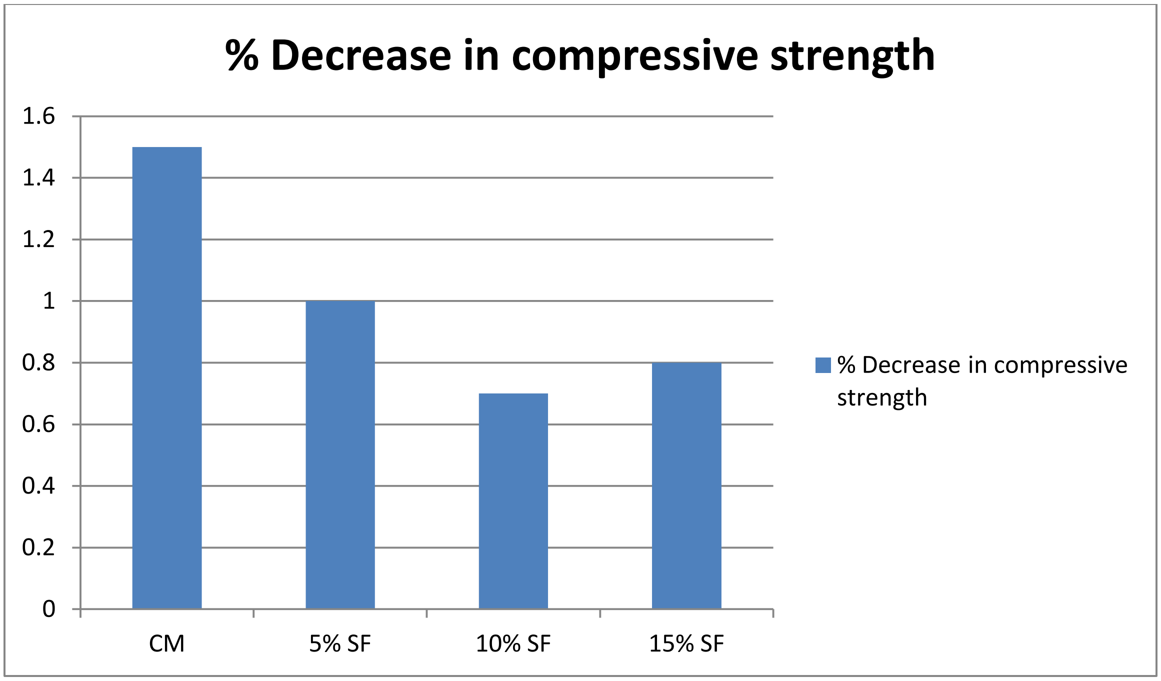

Fig. 5.10 : Percentage loss of compressive strength after 28 days immersion in $MgSo_4$ solution (After 28 days initial curing)

5.2 Metakolin

In this article effects of replacement of metakolin with cement on concrete are discussed. Metakaolin is a valuable admixture for concrete/cement applications that can enhance the performance of cementitious composites through high pozzolanic reactivity, much like silica fume. Metakolin reacts with the calcium hydroxide formed during Portland cement hydration, creating additional cementitious products which modify the concrete structure and enhance its overall mechanical and durability performance. Metakaolin has a particle size that is much finer than cement but not as fine as Silica fume, and it therefore offers better workability and requires smaller amounts of high-range water-reducing admixture to obtain slump comparable to SF concrete. It has a creamier texture, generates less bleed water, and has better finishability than concrete with Silica fume. (Caldarone et al., 1994).

5.2.1 Fresh Concrete Properties

To know the effect of replacement of cement by metakolin in different proportions on fresh concrete properties, the SCC containing different proportion of metakolin were tested for Slump flow, V-funnel, U-Box, and L-box.

The results of fresh properties of all Self-compacting metakolin concretes are included in Table 5.5. 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 600–700 mm, which is an indication of a good deformability.

Table 5.5 : Fresh Concrete Properties (Metakolin)

Mixture ID	**Slump (mm)**	**V-funnel (seconds)**	**L-Box (H2/H1)**	**U-box(H1-H2)**
5% MK	630	10	0.80	34
10% MK	620	11	0.82	40
15% MK	620	12	0.90	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 10-12 seconds. Test results of this investigation indicated that all SCC mixes meet the requirements of allowable flow time. 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.

5.2.2 Compressive Strength Test

To investigate the effect of replacement of metakolin in different proportions with cement on compressive strength, cube specimens of dimensions 150 x 150 x 150 mm are prepared. The replacement level of metakolin is 5%, 10% and 15%. Specimens are cured in water and tested at ages of 7, 28 and 56 days. Test results are given below in Table 5.6 and are represented in Fig. 5.11.

Table 5.6 : Compressive strength of SCC mixes with Metakolin

MIX	**Compressive Strength (N/mm^2)**			**Average Compressive Strength (N/mm^2)**		
	7 days	28 days	56 days	7 days	28 days	56 days
CM	20.7	28.4	31.7	20.6	29.5	31.7
	21.5	30.3	30.9			
	19.6	29.9	32.3			
5% MK	23.0	34.1	37.9	23.9	34.8	37.8
	24.7	35.4	37.1			
	24.1	34.9	38.5			
10% MK	28.1	40.6	44.4	28.6	40.2	44.0
	29.2	41.2	43.8			
	28.7	39.5	44.0			
15% MK	30.4	43.8	46.1	30.3	43.7	46.5
	29.7	43.1	47.2			
	30.8	44.3	46.4			

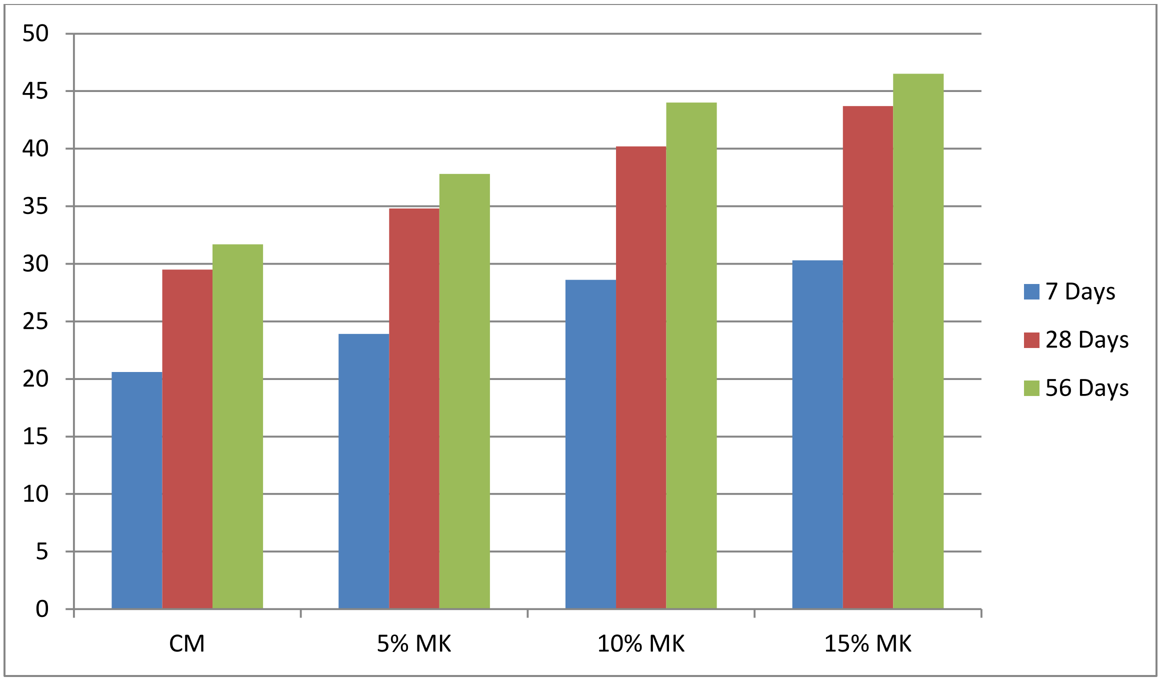

Fig. 5.11 : Compressive strength of metakolin concrete

The water-cement was kept constant at 0.48. The test results indicated that, 5 to 15 percent by weight replacement of metakolin for cement gives better strength at both short and long terms. Compressive strength of metakolin concrete at 28 days compared to control mix was increased by 19 to 46 percent with metakolin added 5 to 15% respectively. Increase in compressive strength in represented graphically below in figure 5.8. Compressive strength of 5% Mk concrete is 23.9, 34.8 and 37.8 N/mm^2 at 7, 28 and 56 days respectively. While that of 15% MK concrete is 30.3, 43.7 and 46.5 at age of 7, 28 and 56 days respectively. There is roughly 25% increase in 28 day strength , when replacement level of metakolin is increased from 5 to 15%. Percentage increase in compressive strength is represented below in Fig. 5.12.

Hassan et al.,(2012) investigated the effect of mtakolin replacement on self compacting concrete and similar results were obtained. Replacement levels was 3, 5, 8, 11, 15, 20, and 25%. Constant w/b ration of 0.4 is used for all mixes. Natural sand and 10 mm maximum size stone were used as fine and coarse aggregates, respectively. High range water reducer (HRWR) similar to Type F of ASTM C 494 was used to adjust the flow ability of the SCC mixtures. Results indicated that there is increase in compressive strength with increase in replacement level of metakolin.

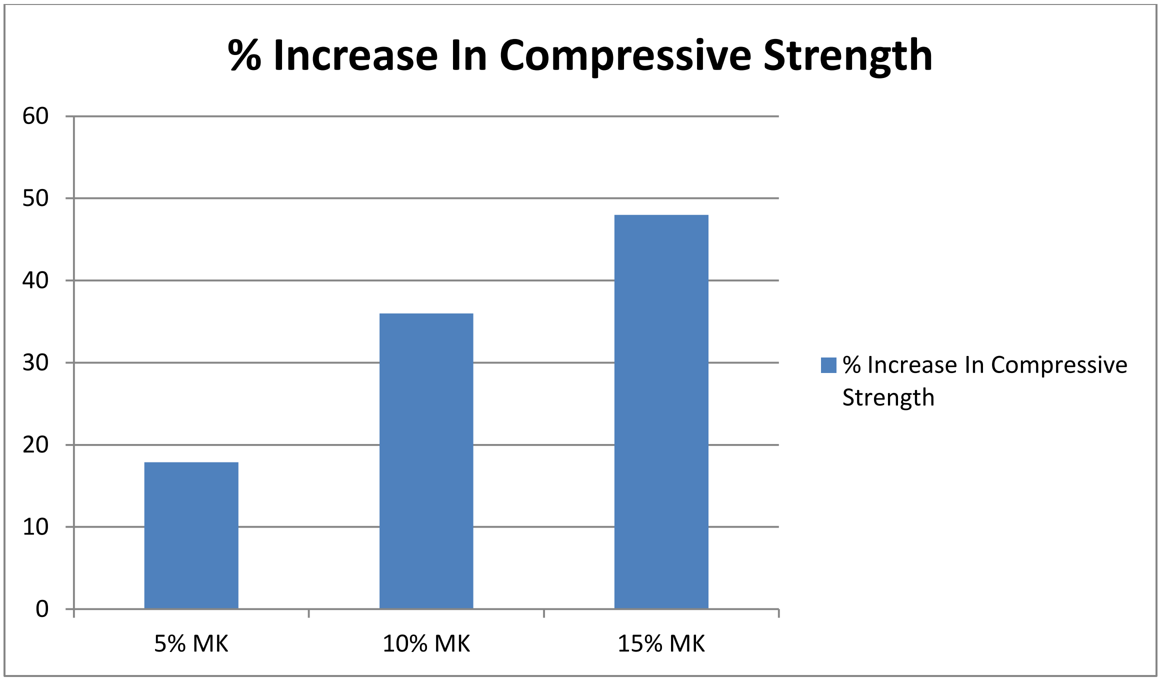

Fig. 5.12 : Percentage increase in Compressive strength

5.2.3 Tensile Strength Test

Split tensile strength studies were carried out at the age of 7, 28 and 56 days. Test results are given below in Table 5.7 and represented in Fig. 5.13.

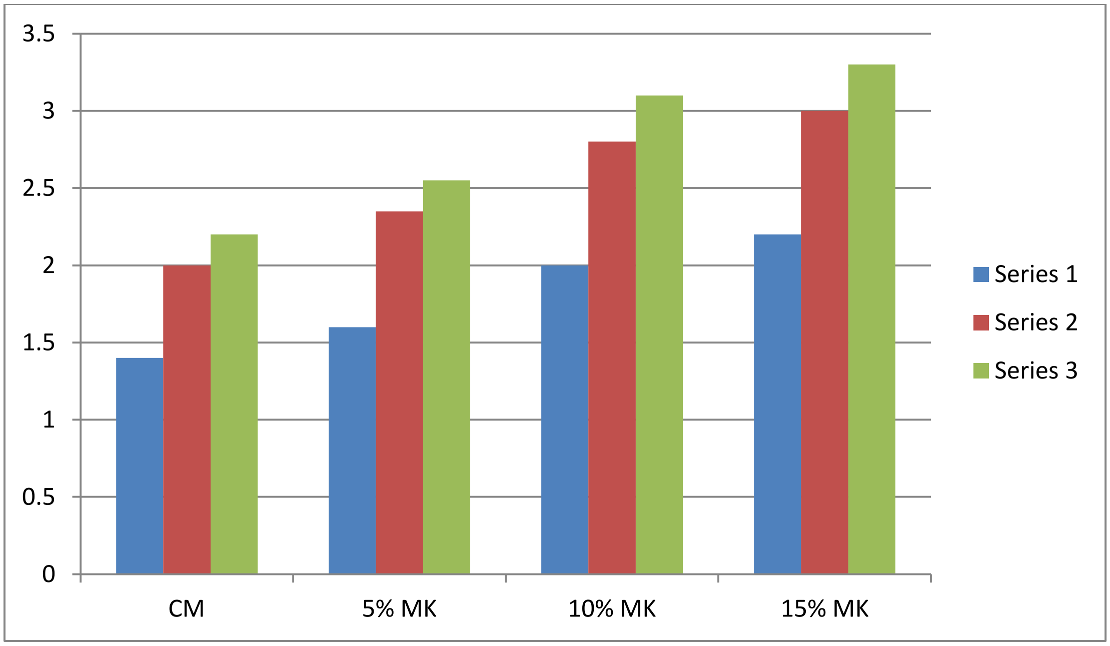

Fig. 5.13 : Splitting tensile strength results of metakolin concrete

Table 5.7 : Splitting tensile strength of SCC mixes with Metakolin

MIX	**Splitting Tensile Strength (N/mm^2)**			**Average Splitting Tensile Strength (N/mm^2)**		
	7 days	28 days	56 days	7 days	28 days	56 days
CM	1.4	1.9	2.1	1.4	2.0	2.2
	1.3	2.1	2.0			
	1.5	2.0	2.2			
5% MK	1.8	2.4	2.45	1.6	2.35	2.55
	1.7	2.25	2.55			
	1.6	2.35	2.55			
10% MK	2.0	2.8	3.2	2.0	2.8	3.1
	1.85	2.7	3.1			
	2.15	2.9	3.0			
15% MK	2.2	3.1	3.2	2.2	3.0	3.3
	2.3	2.9	3.3			
	2.1	3.0	3.4			

When 5% cement is replaced my metakolin, it gives splitting tensile strength of 1.6, 2.35 and 2.55 N/mm^2 at age of 7. 28 and 56 days respectively. At replacement level of 10%, spliiting tensile strength comes to be 2, 2.8 and 3.1 N/mm^2 at age of 7, 28 and 56 days respectively. At age of 28 days there is 18 to 40% increase in splitting tensile strength, when compared to control mix at same age. Control mix has strength of 2 N/mm^2 at age of 28 days. When replacement level is further increased to 15% by weight of cement, there is further increase in splitting tensile strength. It comes out to be 2.2, 3 and 3.3 N/mm2 at age of 7, 28 and 56 days respectively. When compared to control mix at 28 days there is increase of 50%. While there is increase of 27% and 7% splitting tensile strength at 15% replacement, when compared to 5 and 10% replacement levels.

5.2.4 Resistance to sulphate attack of concrete

This test was conducted on 150 x 150 x 150mm cube specimens. The cubes were casted and cured in water for 28 days. Magnesium sulphate solution of strength 5% is used to evaluate sulphate resistance of concrete. Cubes are immersed in solution after 28 days curing, and are tested for compressive strength at 7, 28 and 56 days. Test results are given below in table 5.8. There was decrease in compressive strength of specimens when compared with their normal compressive strengths. But when silica fume and metakolin are used as partial replacements of cement, then this strength loss is minimized.

When this compressive strength is compared with compressive strength of specimens cured in water at same ages, it is found that there is loss of compressive strength. After immersion in solution for 28 days, there is 1.5% loss of strength for control specimen. Control specimen simply cured in water has 56 day strength of 31.7 N/mm^2 while those immersed in solution have strength of 31.2 N/mm^2. When cement is replaced by metakolin, this loss tends to decrease. Strength results are represented below in Fig. 5.14 and given in Table 5.8. At replacement level of 5% metakolin, loss of strength is .8%. Strength of 5% MK specimen after immersion in $MgSo_4$ solution for 28 days is 37.5 N/mm^2, while of the specimen that is cured in simple water is 37.8 N/mm^2. With increase in replacement level upto 10%, loss of strength becomes .7%. When replacement level is further increased, loss of strength decreases further. Strength of 15% replacement specimen after immersion for 28 days in MgSo4 solution is 46.2 N/mm^2. Its loss of strength is approximately .6%, when compared with strength of 15% MK sample cured in water for 56 days. Loss of strength of specimens after immersion for 28 days in $MgSo_4$ solution, when

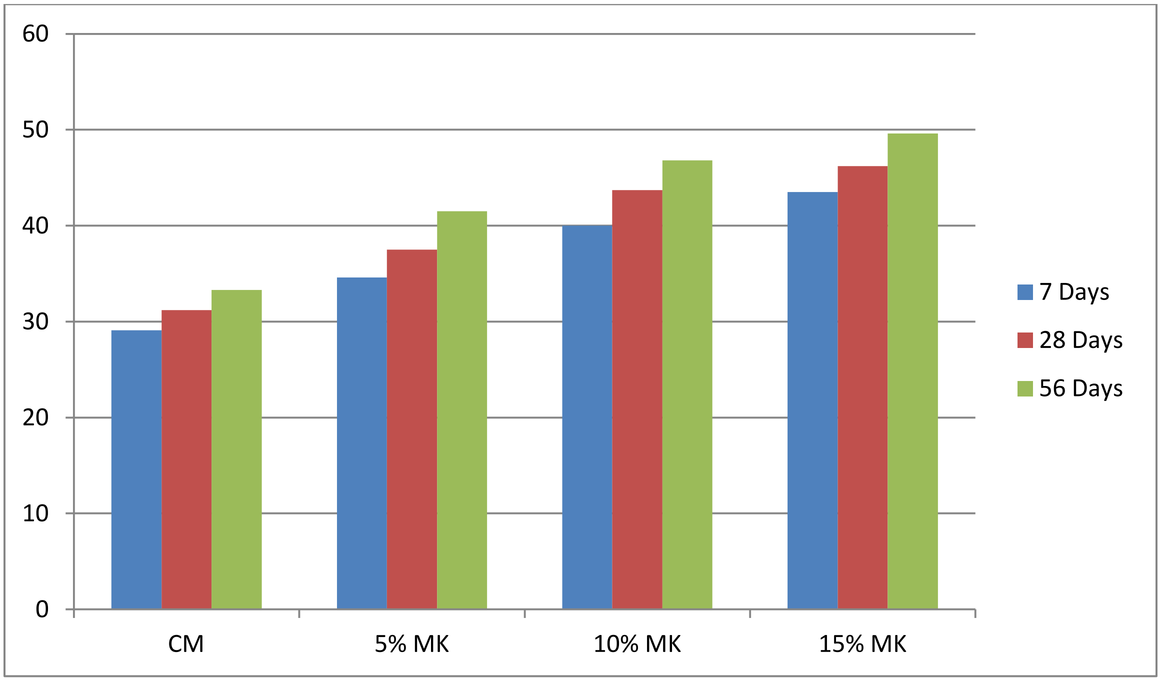

Fig. 5.14 : Compressive strength of metakolin concrete after immersion in 5% $MgSo_4$ solution (After 28 days initial curing)

Table 5.8 : Compressive strength of SCC mixes after immersion in $MgSo_4$ solution

MIX	**Compressive Strength (N/mm^2)(After 28 days curing)**			**Average Compressive Strength (N/mm^2)(After 28 days curing)**		
	7 days	28 days	56 days	7 days	28 days	56 days
CM	29.6	32.3	33.6	29.1	31.2	33.3
	29.1	30.4	32.5			
	28.5	31.0	33.9			
5% MK	35.0	38.0	42.1	34.6	37.5	41.5
	35.6	36.9	40.8			
	33.4	37.6	41.6			
10% MK	40.7	44.5	46.8	40.0	43.7	46.8
	39.4	42.8	45.9			
	39.9	43.9	47.6			
15% MK	43.0	46.1	49.1	43.5	46.2	49.6
	44.2	47.0	49.8			
	43.3	45.5	49.9			

compared with same replacement level specimens cured in simple water for 56 days are represented graphically below in figure 43.

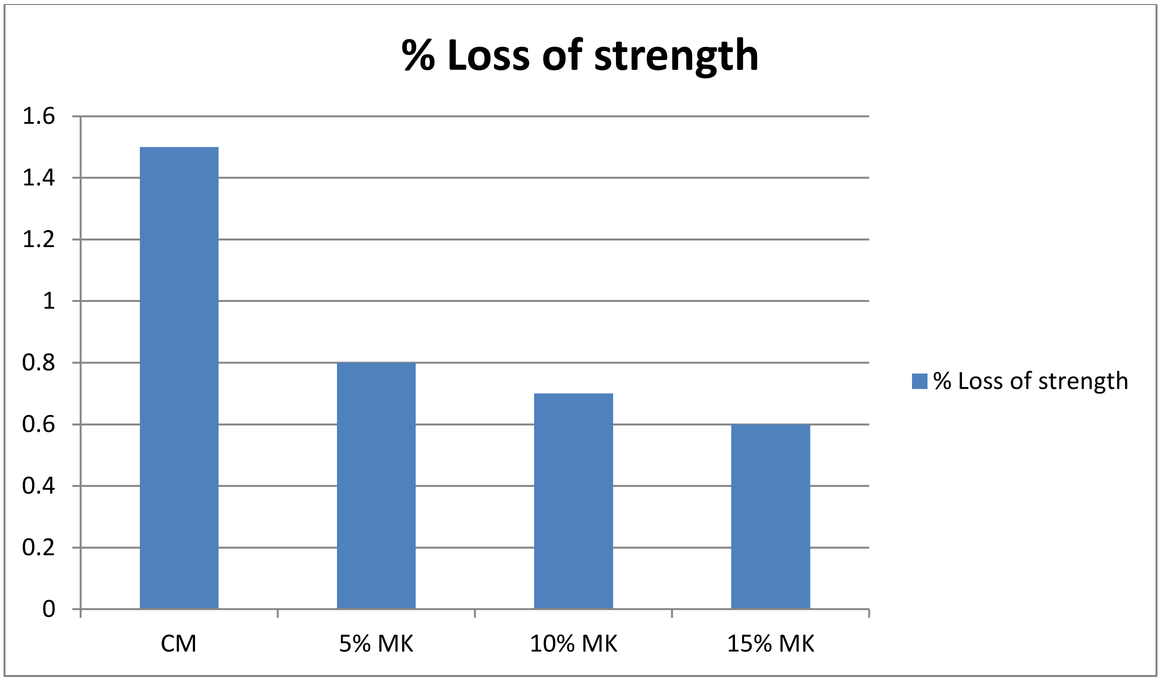

Fig. 5.15 : Percentage loss of compressive strength after 28 days immersion in MgSo₄ solution (After 28 days initial curing)

Uysal And Sumer (2011) investigated effect of different mineral admixtures on the sulphate resisstance of self compacting concrete and obtained similar results. They prepared sixteen series of mix proportions, of which one is control, and fifteen were prepared by replacing Portland cement with different mineral admixtures such as fly ash, granulated blast furnace slag, marble powder, basalt powder and limestone powder. A natural river sand and crushed limestone with a maximum size of 16 mm was used as fine and coarse aggregates respectively. Experimental results of sulphate resistance include reduction in compressive strength loss and visual examination which have been subjected to 10% sodium and 10% magnesium sulphate solutions for 400 days. Incorporation of mineral admixtures decreases the loss of strength.

Hassan et al.,(2012) investigated the effect of mtakolin replacement on self compacting concrete and similar results were obtained. Replacement levels was 3, 5, 8, 11, 15, 20, and 25%. Constant w/b ration of 0.4 is used for all mixes. Natural sand and 10 mm maximum size stone were used as fine and coarse aggregates, respectively. High range water reducer (HRWR) similar to Type F of ASTM C 494 was used to adjust the flow ability of the SCC mixtures. Results indicated that incorporation of metakolin improves durability properties of self compacting concrete,

6. Conclusions

Observations made from the above study, using Silica fume and Metakolin are given below :

- The above results has shown that it is possible to design an SCC mixes incorporating silica fume and metakolin content up to 15%. The SCC mixes have a slump flow in the range of 600–700 mm, V-funnel time in the range of 4–10 s, L-box ratio was greater than 0.8 for all mixes and difference in height of concrete in two compartments in U-box in the range of 5–40 mm.

- The SCC mixes developed compressive strength of 24.6, 27.2 and 25.3 N/mm^2 at 7 days with silica fume replacement of 5, 10 and 15% respectively. While it achieves strength of 35.1, 39.7 and 35.4 N/mm^2 at age of 28 days. At age of 56 days, strength achieved is 38.7, 43.5 and 39.3 N/mm^2 respectively. When metakolin is used as supplementary material in proportions of 5, 10 and 15%, compressive strength achieved at age of 7 days is 23.9, 28.6 and 30.3 N/mm^2. At age of 28 days strength is 34.8, 40.2 and 43.7 N/mm^2 respectively. While at age of 56 days strength achieved is 37.8, 44.0 and 46.5 N/mm^2. Compressive strength increases with increase in percentage of metakolin while in case of silica fume strength increases upto 10% replacement level and then strarts decreasing.

- Splitting tensile strength developed was from 1.7 to 2.0 N/mm^2, 2.5 to 2.75 N/mm^2 and 2.8 to 3.0 N/mm2 at 7,28, and 56 days, respectively with silica fume content. The SCC mixes developed Splitting tensile strengths ranging from 1.6 to 2.2 N/mm^2, from 2.35 to 3.0 N/mm^2 and 2.55 to 3.3 N/mm2 at 7, 28 and 56 days days respectively with metakolin content.
- Use of silica fume and metakolin as replacements of cement, improves sulphate resistance of concrete. When measured in terms of compressive strength loss, there is loss of 1, .7 and .8% strength for 5, 10 and 15% replacement level of silica fume respectively. While in case of metakolin loss of strength is .8, .7 and .6% for replacement level of 5, 10 and 15% respectively.

References

Aitcin, P.,C., (1999). “High performance concrete. London: E & FN Spoon.”

Anagnostopoulos, N.S., Georgiadis, A.S., And Sideris, K.K., (2007). “Carbonation of self compacting concretes produced with different materials.” In: Proceedings of 5th international RILEM symposium on self-compacting concrete. Ghent; pp. 721–727.

ASTM C39. (2005). “Standard test method for compressive strength of cylindrical concrete specimens. Annual Book of ASTM Standards.”

ASTM C 1012, (2002). “Standard test method for length change of hydraulic cement mortar exposed to a sulfate solution. Philadelphia: American Society for Testing and Materials.”

Audenaert, K., Boel, V., And Schutter, G.D., (2002). “Carbonation of Self Compacting Concrete” 6th International Symposium on High Strength/High Performance Concrete, Leipzig, pp. 853-862.

Bartos, J. M., (2000). “Measurement of Key Properties of Fresh Self-compacting Concrete”, CEN/PNR Workshop, Paris.

Bartos, J.M., Marrs, D.L., And Cleland, D.J., (1996). “Production methods and workability of concrete.” pp. 271–284.

Bassuoni, M.,T., And Nehdi, M.,L., (2007). “Resistance of self consolidating concrete to sulphuric acid attack with consecutive pH reduction.” Cement and concrete research, Vol. 37, pp. 1070-1084.

Bonavetti, V.L., Donza, H., Menendez, G., Cabrera,O., And Irassar, E.F., (2003). “Limestone filler cement in low w/c concrete: a rational use of energy.” Vol. 33, pp. 865–871.

Bonen, D.A., (1993). “Microstructural study of the effect produced by magnesium sulfate on plain and silica fume-bearing Portland cement mortars.” Cement and Concrete research, Vol. 23, pp. 541–53.

Boel, V., Audenaert, K., Schutter , De, G., Heirman, G., Vandewalle, L., And Desmet, B., (2005). “Gas permeability of self-compacting concrete.” In: Proceedings of 2nd NorthAmerican conference on the design and use of self-consolidating concrete (SCC) and the 4th international RILEM symposium on self-compactingconcrete.,Chicago; pp. 341–346.

Boukendakdji, O., Kadri, E.,H., And Kenai, S., (2011). “Effect of granulated blast furnance slag and superplasticizer on fresh properties and compressive strength of self compacting concrete.” Cement and concrete composites, In press.

Brouwers, H.J.H., And Radix, H.J., (2005). “Self-compacting concrete: theoretical and experimental study.” Cement and Concrete research; Vol. 35, pp. 2116–36.

BS 3892, (1997). “Pulverized-fuel ash Part 1: specification for pulverized-fuel ash for use with Portland cement”, British Standards Institution.

BS 1881, (1970). “Method for Testing of Hardened Concrete for other than Strength”; Part 5.

Bui, V.K., Montgomery, D., Hinczak, I., and Turner, K., (2002). "Rapid testing method for segregation resistance of self-compacting concrete", Cement and Concrete Research, Vol. 32, pp. 1489-1496.

Caldarone, M.A., Gruber, K.A., and Burg, R.G., (1994). “High-reactivity metakaolin: a new generation mineral admixture”. Concrete International Vol. 16(11), pp 37–40.

Dehn, F., Holschemacher, K., And Weisse, D., (2000). “Self-Compacting Concrete - Time Development of the Material Properties and the Bond Behavior”, LACER No 5, pp. 115-123.

Dehwah, H., A., F., (2012). “Mechanical properties of self compacting concrete incorporating quarry dust powder, silica fume or fly ash.” Construction and building materials, Vol. 26, pp. 547-551.

Dhir, R. K. And Dyer, T. D., (1999). “Modern Concrete Materials: Binders, Additions and Admixtures”, Thomas Telford Publishing, London, UK.

Dietz, J. and Ma, J., (2000). “Preliminary Examinations for the Production of Self-Compacting Concrete Using Lignite Fly Ash”, LACER No.5, pp.125-130.

EFNARC, (2002). “Specifications and Guidelines for Self-Compacting Concrete”, EFNARC, UK , (www.efnarc.org), pp. 1-32.

El-Dieb, A., S., (2009). “Mechanical, durability and microstructural characteristics of ultra hight strength self compacting concrete incorporating steel fibres.” Material and design, Vol. 30, pp. 4286-4292.

Felekoglu, B., (2007). ‘Utilisation of high volume limestone quarry wastes in concrete industry (self compacting concrete case)”, Resources Conservation & Recycling, Vol. 51, pp. 770-791.

Felekogˇlu, B., Turkel, S., And Baradan, B., (2007). “Effect of water/cement ratio on the fresh and hardened properties of self-compacting concrete.” Building and Environment, Vol. 42, pp. 1795–1802.

Ferraris, C. F., Brower, L., Daczko, J., And Ozyldirim, C., (1999). “Workability of Self-Compacting Concrete”, Journal of Research of NIST, Vol. 104, pp. 461-478.

Ferraris, C. F., (1999). “Measurement of the Rheological Properties of High-Performance Concrete”, J. Res. Natl. Inst. Techn., Vol. 104, pp.461-477.

Ganesan N , Indira P.V. & Kumar, S., (2006). “Durability aspects of steel fibre-reinforced SCC”, The Indian Concrete Journal, pp 31-37.

Gerwick, B.C. Jr., (1993). “Construction of Prestressed Concrete Structures”, Second Edition, John Wiley and Sons Inc., pp. 591.

Gesogˇlu, M., And Guneyisi, E., (2011). “Permeability properties of self-compacting rubberized concretes.” Construction and building materials, Vol. 25, pp 3319-3326.

Gesogˇlu, M., Guneyisi, E., And Ozbay, E., (2009). “Properties of self-compacting concretes made with binary, ternary, and quaternary cementitious blends of fly ash, blast furnace slag, and silica fume.” Construction and building material, Vol. 23, pp. 1847-1854.

Grdic, Z. J., Gordana, A., Curcic, T., Iva, M., Despotovic, And Ristic, N. S., (2010). “Properties of self-compacting concrete prepared with coarse recycled concrete aggregate.” Construction and building material, Vol. 24, pp. 1129-1133.

Guneyisi, E., Gesogˇlu, M., and Ozbay, E., (2010). “Strength and drying shrinkage properties of self-compacting concretes incorporating multi-system blended mineral admixtures.” Construction and building material, Vol. 24, pp. 1878-1887.

Hassan, A.A., Lachemi, M., and Hossain, M.A., (2012). “Effect of metakaolin and silica fume on the durability of self-consolidating concrete.” Cement and concrete composites, Vol. 34, pp. 801-807.

IS: 3812, (2003). “Indian standard on pulverised fuel ash – specification. (Part 2). For use as admixture in cement mortar and concrete.” Bureau of Indian Standards, New Delhi (India).

IS 383. (2002). "Specification for coarse and fine aggregates from natural sources for concrete." Bureau of Indian Standards, New Delhi (India).

IS: 516 , (1959). "Methods of tests for strength of concrete." Bureau of Indian Standards, New Delhi (India).

Kathirvel, P., Kapilarasan**,** M.**,** Hameed**,** M.S.**,** And Sekar, A.S.S., (2010). "Effect of Sulphate Attack on Self compacting Concrete." NBM Constructions Information, NBM Media Pvt. Ltd.

Khayat, K.,H., and Aitcin, P.,C., (1987). "Silica Fume A unique Supplementary Cementitious Material," Mineral Admixture in Cement and Concrete, Vol.4.

Khayat, K.H. And Guizani, Z., (1997). "Use of Viscosity-Modifying Admixture to Enhance Stability of Fluid Concrete", ACI Materials Journal, Vol. 94, pp.332-340.

Khayat, K.H., Assaad, J., And Daczko J., (2004). "Comparison of Field-oriented Test Methods to Assess Dynamic Stability of Self-Consolidated Concrete", ACI Materials Journal, Vol. 101, pp. 168-176.

Khayat, K.H., (1999) "Workability, Testing and Performance of Self Consolidated Concrete", ACI Materials Journal, Vol. 96, pp. 346-352.

Khatib, J.M., (2005). "Properties of concrete incorporating fine recycled aggregate." Cement and Concrete research; Vol. 35, pp. 763–769.

Khunthongkeaw, J., Tangtermsirikul. S., And Leelawat, T., (2006). "A study on carbonation depth prediction for fly ash concrete." Construction and Building material; Vol. 20, pp. 744–753.

Khaloo, A. R., And Houseinian, M. R., (1999). "Evaluation of properties of silica fume for use in concrete." International Conference on Concretes, Dundee, Scotland.

Kosmatka, S. H., Kerkhoff, B., And Panarese, W. C., (2002). "Design and Control of Concrete Mixtures", 14th Edition, Portland Cement Association.

Kostuch, J., A., Walters, G.,V., and Jones, T.,R. (1993). "High performance concrete incorporating metakaolin: a Review." E & FN Sponsor, pp. 1799-1811.

Kou, S.C., And Poon, C.S., (2009). "Properties of self-compacting concrete prepared with coarse and fine recycled concrete aggregates." Cement and concrete composites, Vol 31, pp. 622-627.

Krieg, W., (2003). “Self-Compacting Concrete: Definition, Development, and Applications”, A Technical Paper Presented in the Meeting of the ACI, Saudi Arabia Chapter, Eastern Province.

Kurita, M., And Nomura, T., (1998). “Highly-flowable steel fiber-reinforced concrete containing fly ash.” In: Malhotra VM, editor. Am Concr Inst SP 178, pp. 159–75.

Kim, J.K., Han, S.H., Park, Y.D., and Noh, J.H., (1998). "Material Properties of Self-Flowing Concrete", Journal of Materials in Civil Engineering, Vol. 10, pp. 244-249.

Lachemi, M., Hossain, K.M.A., Lambros, V., Nkinamubanzi, P.C., And Bouzoubaa, N., (2004). "Performance of new viscosity modifying admixtures in enhancing the rheological properties of cement paste", Cement and Concrete Research, Vol. 34, pp. 185-193.

Lee, S.T., Moon, H.Y., Hootona, R.D., And Kim, J.P., (2005). “Effect of solution concentrations and replacement levels of metakaolin on the resistance of mortars exposed to magnesium sulfate solutions.” Cement and Concrete research; Vol. 35, pp. 1314–1323

Mata, L. A., (2004). “Implementation of Self-Consolidating Concrete (SCC) for
Prestressed Concrete Girders, MS Thesis, North Carolina State University.”

Mindess, S., Young, J.F., And Darwin, D., (2003). Concrete. 2nd ed. New Jersey: Prentice Hall.

Nanthagopalan, P., And Santhanam, M., (2011). “Fresh and hardened properties of self-compacting concrete produced with manufactured sand.” Cement and concrete composites, Elsevier Ltd., Vol. 33, pp. 353-358.

Naik, T. R., And Singh, S., (1997). “Influence of fly ash on setting and hardening haracteristics of concrete systems.” Materials Journal, Vol. 94, pp.355-360.

Nehdi, M., Pardhan, M., And Koshowski, S., (2004). "Durability of self-consolidating concrete incorporating high-volume replacement composite cements". Cement and Concrete Research, Vol. 34, pp. 2103-2112.

Okamura, H. and Ouchi, M., (2003). “Self-compacting concrete”, Journal of
Advanced Concrete Technology, Vol. 1, pp. 5-15.

Okamura, H., (1997). “Self-Compacting High-Performance Concrete”, Concrete International, Vol. 19, pp. 50-54.

Ouchi, M., Hibino, M., Sugamata, T., And Okamura, H., (2001). “A quantitative evaluation method for the effect of superplasticizer in self-compacting concrete", Transactions of JCI, pp. 15-20.

Ouchi, M., Hibino, M., And Okamura, H., (1996). "Effect of Superplasticizer on Self-Compactability of Fresh Concrete", TRR 1574, pp.37-40.

Ouchi, M., And Hibino, M., (2000). "Development, Applications and Investigations of Self-compacting Concrete".

Persson, B., (2003). "Sulphate resistance of self compacting concrete." Cement and concrete research, Vol. 33, pp. 1933-1938.

Ramachandran, V.,S., (1984). "Concrete Admixtures Handbook, Properties, Science, and Technology." Noyes Publications.

RILEM Committee CPC-18, (1988). "Measurement of hardened concrete carbonation depth." Material and Structures, pp. 18:453–455.

Sahmaran,M., Yaman,O.I., And Tokyoy,M., (2009). "Transport and mechanical properties of self consolidating concrete with high volume fly ash." Cement & Concrete Composites; Vol. 31, pp. 99–106.

Siddique, R., Aggarwal, Y., Aggarwal, P., Kadri, E., Bennacer, R., (2011). "Strength, durability, and micro-structural properties of concrete made with used-foundry sand (UFS)." Construction and building material; Vol. 25, pp. 1916-1925.

Siddique, R. (2011). "Properties of self-compacting concrete containing class F fly ash". Materials and Design, Vol. 32, pp. 1501-1507.

Sisomphon, K., Franke, L., (2006). "Carbonation rates of concretes containing high volume of pozzolanic materials." Cement and Concrete research; Vol. 37, pp. 1647–1653.

Song, H.W. And Kwon, S.J., (2007). "Permeability characteristics of carbonated concrete considering capillary pore structure." Cement and Concrete research, Vol. 23, pp. 909–915.

St John, D., A. (1998). "Concrete Petrography, A handbook of investigative techniques." Wiley & Sons, New York.

Taylor H. F.W., (1997). "Cement chemistry". 2nd ed. London: Thomas.

Uysal, M., And Sumer, M., (2011) “Performance of self-compacting concrete containing different mineral admixtures.” Construction and building material, Vol. 25, pp. 4112-4120.

Xie, Y., Liu, B., Yin, J., And Zhou, S., (2002). “Optimum mix parameters of high–strength selfcompacting concrete with ultrapulverised fly ash.” Cement and Concrete research; Vol. 32, pp. 477–480.

Yahia, A,, Tanimura, M., Shimabukuro, A., And Shimoyama, Y., (1999). “Effect of rheological parameters on self compactiblity of concrete containing various mineral admixtures.” In: Proc of the first RILEM international symposium on self compacting concrete, Stockholm. pp. 523–535.

Zhimin W., Yunguo Z., Jianjun Z., And Yining D., (2009). “An experimental study on the workability of self-compacting lightweight concrete.” Construction and building material, Vol. 23, pp. 2087-2092.

Zhu, W., Gibbs, C. J., And Bartos, P. J. M., (2001). "Uniformity of in situ properties of self compacting concrete in full-scale structural elements", Cement & Concrete Composites, Vol. 23, pp. 57-64.

Zongin, Li., Bin, Mu., and Stanley, N.,C., (1999). “Systematic study of properties of extrudates with incorporated metakaolin or silica fume.” ACI Mater Journal, Vol. 96(5), pp. 574-80.