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SELF-COMPACTING CONCRETE

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Abstract

Concrete gains the strength by hydration process. It has a mixer of coarse aggregate, fine aggregate, cement and water. We have used the admixtures for some changing the properties of cement. To the continue hydration, the relative moisture inside the concrete should be 85% for this curing to be continue. Curing is supply of water or by steam from outside (External Curing) or from inside (with help of any moisture containing agent i.e. Self-Curing). In this study, we study the review of previously published papers on self-curing concrete and find out suitable moisture containing agents and some another Admixtures to improve moisture holding capacity of concrete. The effect of self-curing concrete of compressive and split tensile strength is also study.

Key words: Compressive strength, Split tensile strength, Steel fibers, Self-curing concrete, Pre-saturated dust, curing, PVA, PEG-400, Alccofine

CHAPTER-1.

INTRODUCTION

1.1 SCOPE OF RESEARCH

Concrete is the most consumed construction material for buildings at present. The achievement of designed strength and durability of concrete relies largely on sufficient compaction during placement. Inadequate compaction can dramatically lower the performance of mature concrete in-situ. Therefore, to ensure adequate compaction and homogeneity of the cast concrete and to facilitate its placement especially in structures with congested reinforcement and restricted areas, self-compacting concrete has been introduced.

It all started around 1988 at Tokyo University when Okamura et al. (1998) established the basic description of SCC. The history of self-compacting concrete (SCC) dates back to late 1980s. SCC concepts originally were thought to be a tool to enhance long-term durability of structures having members with congested reinforcements. It has generated tremendous interest since its inception. It has been considered as the greatest breakthrough in concrete technology for many decades due to the improved performance and working environment.

SCC is a concrete that is capable of self-compacting, occupies all the space in the formwork without any external effort (in the form of mechanical vibration, floating, poking etc.). For the concrete to occupy the full space, flowing through the formwork, without any external effort, it has to have an acceptable level of passing ability, filling ability and stability. Because of the heterogeneous nature of concrete, its high fluidity and the fact that it contains materials with different specific gravities, cohesiveness becomes an issue, as it is very difficult to keep its constituents in a cohesive form where higher mass particles tend to settle down. This problem however can be tackled by adding larger amounts of finer material. Owing to its excellent user-friendly characteristics, SCC is a highly attractive alternative today in traditional construction industry.

Depending on its composition, SCC can have a wide range of different properties; from a normal to an ultra-high compressive strength, from a poor to an extremely high durability. The mixture of SCC is strongly dependent on the composition and characteristics of its

constituents in its fresh state. The properties of SCC in its fresh state have a great influence on its properties in the hardened state. Therefore it is critical to understand its flow behaviour in the fresh state. Since the SCC mix is essentially defined in terms of its flow-ability, the characterisation and control of its rheology is crucial for its successful production.

This is even more relevant if the fibres are added to SCC. Self-compacting high and ultra-high performance fibre reinforced concretes (SCHPFRC/SCUHPFRC) must maintain their flow- ability and passing ability despite the presence of a large volume fraction of fibres. This presents a challenge which makes the control of rheology crucial for the successful production of SCHPFRC/SCUHPFRC. The definition of SCHPFRC/SCUHPFRC changes from country to country and from time to time. However, SCHPFRC has a characteristic strength in excess 100 MPa and that of SCUHPFRC is in excess of 140 MPa.

The flow of SCC with or without fibres is best described by the Bingham constitutive model. This model contains two material properties, namely the yield stress and the plastic viscosity. It is known however that the yield stress of SCC mixes is low in comparison with normal vibrated concretes and remains nearly constant over a large range of plastic viscosities. The viscosity of a homogenous viscous fluid such as the cement paste can be measured accurately which cannot be said of any SCC.

The prediction of SCC filling behaviour is very difficult especially in the presence of reinforcing steel and in formworks of complex shapes. However, an understanding of the behaviour and the flow characteristics is crucial to achieving a high quality SCC. The most cost-effective way to gain such an understanding is by performing numerical simulations, which will enable us to fully understand the flow behaviour of SCC with or without steel fibres and to reveal the distribution of larger aggregate particles and of fibres and their orientations inside the formworks. The accurate picture can only be gained by using the three-dimensional flow simulation which shows the actual distribution of fibres and their orientations during the flow.

Research objectives

The objectives of this thesis are as follows:

- To produce self-compacting concrete (SCC) mixes of varying strengths and performances with or without steel fibres. The aim is to investigate how the proportions of solids and liquids, the amount of super-plasticiser, and the steel fibres need to be selected in order to produce SCC mixes with the right flow-ability, passing ability and segregation resistance.

- To estimate the plastic viscosity of the developed SCC mixes using micromechanical principles. This plastic viscosity, together with the yield stress of the mix, is needed in the numerical simulation of SCC flow in moulds of different shapes and sizes.
- To simulate the 3-dimentional flow of the non-Newtonian viscous SCC mixes using smooth article hydrodynamic approach in two standard test configurations, namely the slump flow and L-box tests using appropriate computational strategies. To simulate also the slump flow test as a homogenous mass in axisymmetric configuration.
- To monitor the distribution of larger aggregate particles of different sizes during the flow.
- To provide a simple method to assess the orientation and distribution of short steel fibres in self-compacting concrete mixes during flow.
- To proportion self-compacting mixes of varying strengths and performance with and without steel fibres that have the correct flow and passing ability using the computational flow modelling technique at the mix design stage.

1.2 Research methodology

To achieve the above objectives research was undertaken in four stages:

First, self-compacting concrete (SCC) mixes of varying strengths and performances were developed to meet the flow-ability, passing ability and segregation resistance criteria. The design of SCC mixes followed the traditional trial-and-error approach, Using the slump cone, J-ring and L-box tests on trial mixes, until the mix was found that met the flow-ability and passing ability criteria and had no visible signs of segregation. The plastic viscosity of the SCC mixes so developed with or without fibres was then estimated using a micromechanical procedure and the known plastic viscosity of the cement paste which can be measured accurately. For this, concrete was regarded as two-phase suspension of solid and liquid phases, and the plastic viscosity was estimated from a two-phase model in several stages until all the ingredients of SCC have been accounted for. By adding steel fibres, the plastic viscosity increases significantly; this increase was quantified using a micromechanical model.

Second, a three-dimensional and an axisymmetric Lagrangian smooth particle hydrodynamics (SPH) method has been used to model the flow of self-compacting concrete (SCC). The constitutive behaviour of this non-Newtonian viscous fluid is described by a Bingham-type model. The 3D simulations of SCC without fibres are focused on the distribution of large aggregates (larger than or equal to 8 mm) during the flow. The simulation results are in very good agreement with available experimental data.

Third, a simple method has been developed to assess the orientation and distribution of short steel fibres in self-compacting concrete mixes during flow. In this stage, a three-dimensional Lagrangian smooth particle hydrodynamics (SPH) method has been used to model the flow of self-compacting concrete (SCC) with short steel fibres. This simulation is focused on the distribution of fibres and their re-orientation during the flow.

Fourth, the SPH simulation technique was used at the mix design stage to proportion the mixes of SCC mixes of different strength and performance that meet the flow ability, passing ability requirements and have the desired plastic viscosity.

CHAPTER-2.

SELF-COMPACTING CONCRETE

2.1 Introduction

Reinforced concrete is one of the most versatile and widely used construction materials. With the demand increasing for reinforced concrete structures in the modern society to meet the needs of new developments, increasing population and new ambitious structural design ideas, the reinforcement in concrete structures is becoming more dense and clustered. The heavy and dense reinforcement can raise problems of pouring and Compacting the concrete. The concrete must be able to pass the dense rebar arrangement without blocking or segregating. The design of such concrete is very challenging because poor placement and the lack of good vibratory compaction can lead to the inclusion of voids and loss of long term durability of concrete structures. This has been a concern for engineers for many years.

During the last decade, concrete technology has made an enormous advance through the introduction of self-compacting concrete (SCC). Self-compacting or self-consolidating concrete is a relatively new generation of high-performance concrete that is able to achieve impressive deformability and homogeneity in its fresh state, filling all the space around the reinforcement, passing through dense reinforcing steel bars while compacting under its own weight without any external vibration.

SCC with its outstanding properties, impressive deformability, gives designers and architects more freedom of creativity that was not possible previously. Lighter and slender members can be made from SCC, larger span bridges can be developed, and underwater structures can be built, making SCC a highly promising material for the future of the in-situ and pre-cast construction industries. Since its early use in Japan, SCC has now started to be an alternative to vibrated concrete across the world in such areas where normal vibrated concrete is difficult or impossible to pour and vibrate. However those applications are still few and vibrated concrete is still considered as the standard concrete. As more and more investigations are done into SCC, it is likely to move from being a fringe technology to becoming a concrete of choice for construction because of reduced health concerns, i.e. no vibration-induced noise.

In this chapter, a general overview of the properties and applications of SCC will be given, highlighting the influence of materials used on its characteristics in the fresh and hardened states. Fibre reinforced SCC will also be reviewed with an emphasis on steel fibres. Finally, the testing methods of SCC in its fresh state will be 422ummarized, together with its rheological properties.

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2.2 History of development

In the mid-1980s, research undertaken into underwater placement technology within the UK, North America and Japan led to the development of concrete mixes with a high degree of washout resistance. However, the creation of durable structures from such mixes required adequate compaction by skilled workers. At the same time in Japan, a gradual reduction in the number of skilled workers in the construction industry was leading to a reduction in the quality of construction work, with subsequent knock-on effects on concrete durability (Okamura et al., 1998). One solution to overcome the durability problems in concrete structures independently of the quality of construction work was to use self-compacting concrete (SCC) (Okamura and Ouchi, 2003).

Its use was first proposed by Okamura (1986) who also conducted a fundamental study on the workability of SCC. The first prototype SCC was completed in 1988 at Tokyo University, using constituent materials readily used in conventional vibrated concrete (Ozawa et al., 1989). The main reasons for the employment of SCC were to shorten the construction time, to avoid vibrating the confined zones which are rather difficult to reach and to eliminate noise caused by vibration (Okamura and Ouchi, 2003).

Although Japan was the predominant user in the early years of development, the technology spread then to Europe starting from Sweden to other Scandinavian countries at the end of the 1990s (Billberg, 1999) . In Denmark, SCC has been applied in both ready-mix and pre-cast industry with an annual production reaching approximately 20% and 30%, respectively of the total concrete production (Thrane et al., 2004). Other countries, such as UK, France, Germany, USA and the Netherlands have also been developing and using the material (Ouchi et al., 2003; Bennenk, 2005) with a temporary stagnation. One reason for this stagnation appears to be the lower segregation resistance of SCC compared with vibrated concrete (Thrane et al., 2004).

In the last two decades, self-compacting concrete has been developed further, utilizing various materials such as pulverized-fuel ash (PFA), ground granulated blast furnace slag (GGBS) and condensed silica fume (CSF). SCC has gained wide interest especially for structures with very complicated shapes, difficult casting process and congested reinforcement. In spite of this, the overall production is still relatively small compared to conventional concrete (Gaimster and Dixon, 2003), the global gap that has been always present in the market for such a concrete indicates that in the future there is likely to be an even greater demand for all types of SCC.

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2.3 Self-Curing concrete definition

The British Standard (BS EN 206-9, 2010) defines “SCC is the concrete that is able to flow and compact under its own weight, fill the formwork with its reinforcement, ducts, boxouts etc, whilst maintaining homogeneity”.

Other researchers (Ozawa et al., 1989; Bartos and Marrs, 1999; Khayat, 1999) have defined SCC in almost the same terms as a highly flow-able concrete that should meet the following requirements:

- **Flow-ability**: SCC should flow under its own weight and fill all parts of formwork without any external aid or vibration.
- **Passing ability**: SCC should pass through heavy reinforcing steel bars.
- **Segregation resistance:** SCC should maintain its homogeneity without any migration or separation of its large components (aggregates or/and fibres).

2.4 Advantages and disadvantages of using SCC

The use of SCC on site offers many advantages:

- **Eliminating vibration and lower noise level:** This will certainly put less physical demands on site workers, something that is clearly a desirable objective, including preventing "white finger" syndrome, which is mainly related to the vibrating equipment.
- **Easy placement and filling:** the impressive filling ability, flow-ability and passing ability of SCC eases placement significantly even with very complex shaped structures and where heavy reinforcement or very long formwork is involved, and eliminate honeycombing, blow holes and grout loss.
- **Better surface finish:** SCC ensures a uniform architectural surface finish with little to no remedial surface work as illustrated in Figure 2.1.

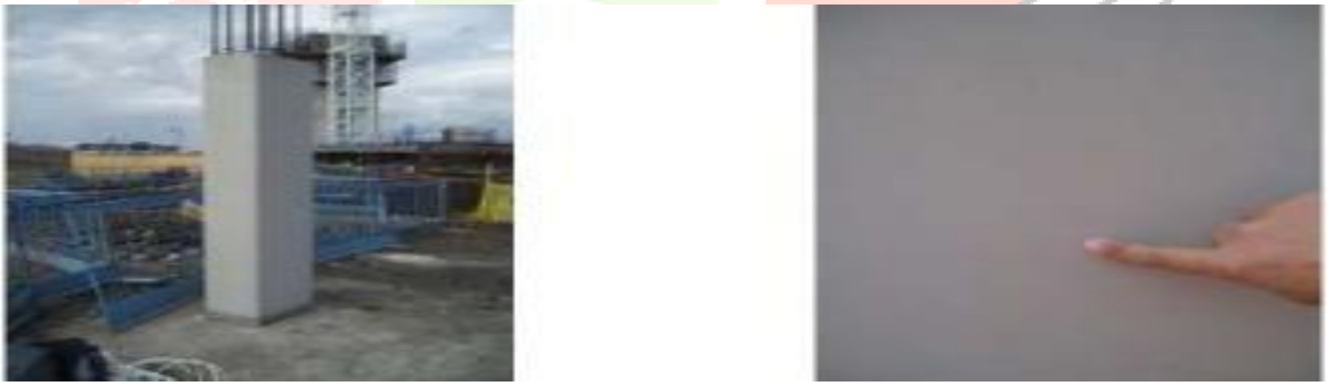


Figure 2.1: Surface finish for a column using SCC with no repairs or "rubbing down"

- **Reduce manpower and construction time:** SCC can be placed at a faster rate with no vibration and less screeding resulting in reducing manpower and saving construction time.
- **Improve durability:** due to the dense matrix of SCC and the high consolidation and bond around reinforcement, the structural durability is improved.
- Among sixty eight case studies of the applications of self-compacting concrete (SCC), which were published from 1993 to 2003, the period of increasingly widespread use of SCC in many countries, Domone (2006) reported that 67% were using SCC for technical advantages where vibration is either difficult or impossible due to the heavy reinforcement or

inaccessibility, 14% were for economical reason to reduce labour work and construction time, while 10% were for new types of structure such as thin sections, pre-cast units and steel/concrete composite. The rest of the cases involved environmental causes including reducing noise level and improving working conditions.

- We should however also mention the possible disadvantages of using SCC compared with conventional concrete can include the high cost of materials which can subsequently
- Be overcome by the low cost of labour. Another disadvantage can be related to the nature of SCC, because of its high fluidity, handling and transporting SCC becomes a bit delicate, although the outstanding results would definitely overcome these disadvantages.
- 2.5 Fresh state properties of self-compacting concrete

2.5.1 Deformability (flow and filling ability)

Deformability refers to the ability of SCC mix to deform and undergo changes in shape with completely filling all areas and corners of the formwork horizontally and vertically whilemaintaining its homogeneity. The deformability of SCC is characterized by the concrete's fluidity and cohesion, and mainly assessed using the slump flow test described later in this Chapter.

Kennedy (1940) proposed the 'Excess Paste Theory' as a way to explain the mechanism governing theworkability of concrete. Kennedy states that there must be enough paste to cover the surface area of the aggregates, and that the excess paste serves to minimize the friction among the aggregates and give better flow-ability. Without the paste layer, too much friction would be generated between the aggregates resulting in extremely limited below workability

Figure 2.2: Excess paste layer around aggregates

Figure 2.2 shows the formation of cement paste layers around aggregates. The thickness of the paste layer can be best related to the diameter of the aggregates (Oh et al., 1997).

2.5.2 Passing ability

Passing ability refers to the ability of SCC mix to pass through congested reinforcement without blocking, whilst maintaining good suspension of coarse particles in the matrix, thus avoiding arching near obstacles and blockage during flow. The J-ring and L-box tests are the most common methods used to assess this property (see Figures 2.25 and 2.26).

The probability of blocking increases when the volume fraction of large aggregates and/or fibres increases. The size of aggregates, their shapes and their volume fraction influence the passing ability of SCC, moreover, the presence of fibres especially long and hooked or crimped ends make self-compacting fibre reinforced concrete (SCFRC) more difficult to pass through reinforcement.

kamura and Ouchi (1999) reported that the potential of collision and contacts between particles increases as the distance between particles decreases; which therefore results in an increase in the internal stresses when concrete is deformed, particularly near obstacles causing blockage.

Research shows that the energy required for flowing is consumed by the increase of internal stresses. Limiting the coarse aggregate content whose energy consumption is high can effectively reduce the risk of blockage. Figure 2.3 shows how normal stress can be generated due to the approach of coarse aggregate particles near obstacles.

Highly viscous paste also prevents localized increases in internal stress due to the approach of coarse aggregate particles (Okamura and Ouchi, 1999) and therefore increases the passing ability of SCC. Roussel et al. (2009) state that highly fluid SCC could be more prone to have its coarsest particles blocked in highly reinforced zones, which is related to the instability of the material, and to the increases in the local volume fraction of coarse aggregates near an obstacle as shown in Figure 2.4; in this case, the material is too fluid to carry its own particles during the flow.

Blocking can be also increased as the gaps between steel bars are reduced. The spacing between bars is typically recommended to be 3 times the maximum aggregate size (EFNRC, 2005). For fibre-reinforced concrete, the bars should be placed 1 to 3 times the maximum fibre length (Koehler and Fowler, 2003).

2.5.3 Segregation resistance (homogeneity/cohesiveness)

Segregation resistance refers to the ability to retain the coarse components of the mix and the fibres in suspension in order to maintain a homogeneous material. Stability is largely dependent on the cohesiveness and the viscosity of the concrete mixture which can be increased by reducing the free water content and increasing the amount of fines (Khayat et al., 1999).

Segregation resistance is largely controlled by viscosity; therefore ensuring a high viscosity can prevent a concrete mix from segregation and/or bleeding. Bleeding is a special case of segregation in which water moves upwards by capillary action and separates from the mix. Some bleeding is normal for concrete, but excessive bleeding can lead to a decrease in strength, high porosity, and poor durability particularly at the surface (Douglas, 2004).

Two basic methods can ensure adequate stability; the first approach is based on the Japanese method. It uses a super-plasticiser (SP), low water/cement ratio, high powder content, mineral admixtures, and low aggregate content. The second approach is based on incorporating a viscosity-modifying admixture (VMA), low or moderate powder content and super-plasticiser (Bonen, 2004).

2.6 How does SCC defer from vibrated concrete

SCC consists of cement, aggregates, water and admixtures which are quite similar to the composition of conventional vibrated concrete, however, the reduction of coarse aggregates, the large amount of fines, the incorporation of super-plasticizer, the low water to cement ratio, is what led to self-compactability. Figure 2.5 shows a general comparison between mix proportions of self-compacting concrete (SCC) and vibrated concrete (VC).

What makes SCC unique is the migration of air bubbles to the surface without any vibration which is mainly due to the dense matrix, mix proportion and the material characteristics. The smooth passing ability through reinforcement bars and the impressive filling ability of all the formwork without any segregation or bleeding are remarkable, even in narrow structural elements with complicated shapes and heavy reinforcement, thanks to the balance between high fluidity and moderate viscosity. All these properties in the fresh state would lead to a high strength and durable concrete in the hardened state; especially after adding steel fibres, the performance becomes distinctly high.

2.6 Mechanisms of achieving SCC

In the fresh state, SCC should achieve high flow-ability as well as rheological stability (see section 2.15), which means it must be as fluid as possible in the fresh state to fill under its own weight all the far reaching corners in the form work and pass through heavy reinforcement without segregation. The methodology of selecting the right amount of materials and admixtures is crucial to achieve this goal. The following three main rules have been suggested by Okamura and Ouchi (2003):

- Limiting aggregate content.
- Using super-plasticiser.
- Reducing water-powder ratio.

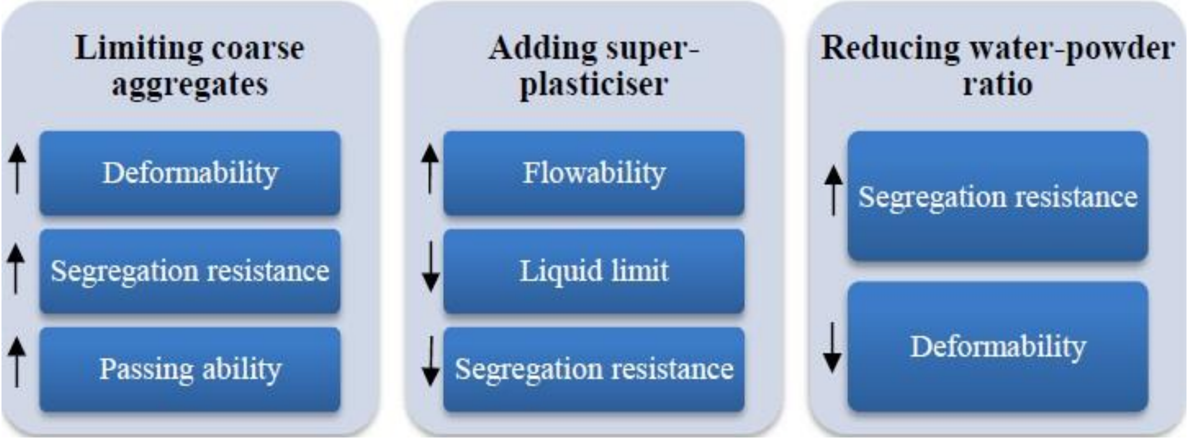


Figure 2.6: Mechanisms of achieving self-compactability. increases, decreases

Figure 2.6 illustrates the three main rules of achieving self-compactability and the influence of each rule on the mechanism of achieving self-compactability

Limiting aggregate content: The friction between the aggregates limits the spreading and the filling ability of SCC. By reducing the volume and the maximum size of coarse aggregates, and replacing crushed aggregates with round ones the passing ability of SCC in congested areas can be increased, thus improving the workability and optimizing the packing density of skeleton. High amount of super-plasticiser: Achieving a highly

flowable mix would conflict with keeping the homogeneity at an acceptable level. The mechanism of achieving this is by the dispersion effects of super-plasticiser on flocculated cement particles, by reducing the attractive forces among them. An optimum amount is necessary as a high amount would result in segregation and a low amount would compromise the fluidity. Obtaining a good degree of cohesiveness can guarantee a considerable improvement in the overall performance (Kwan and Ng, 2010).

High paste volume: SCC contains a high volume of paste, the role of which is to maintain aggregate separation (Tviksta, 2000). Okamura and Ouchi (2003) indicated that the internal stresses can increase when concrete is deformed, particularly near obstacles. The energy required for flowing is consumed by those increased internal stresses, resulting in blockage. Also, paste with high viscosity prevents localized increases in internal stresses due to the approach of coarse aggregate particles. A high amount of fine particles increases the workability and cohesiveness while simultaneously reducing the interlocking of coarse particles which could result in a blocking behaviour (Khayat, 2000). The necessity of including this large amount of fines requires that there should be cement replacement materials such as GGBS, silica fume, fly ash...etc., in order to avoid excessive heat generation.

Using viscosity modifying agents (VMA): These products are generally cellulose derivatives, polysaccharides or colloidal suspensions. The use of VMA gives the same effect as the fine particles in minimising bleeding and coarse aggregate segregation by thickening the paste and retaining the water in the skeleton. For normal strength SCC with high water to binder content, the introduction of such products seems to be justified. On the other hand, they may be less useful for high performance SCC with low water to binder ratio. Viscosity agents are assumed to make SCC less sensitive to water variations. Because of the small quantities of viscosity agents required, however, it may be difficult to achieve accuracy of dosage (Tviksta, 2000).

2.6 SCC Mix design

Over the last decade, extensive research has been devoted to achieve self-compactability. Three different types of mixes can be distinguished: "Powder- type" by increasing the powder content, "VMA-type" using viscosity modifying admixture (VMA) and "Combined- type" by increasing powder content and using a viscosity agent in consideration of structural conditions, constructional conditions, available material, restrictions in concrete production plant, etc.

2.7 Powder-Type SCC

Okamura and Ozawa (1995) proposed a simple mix proportioning system for SCC mix (Figure 2.7). Their main ideas were to fix the coarse aggregate content at 50% of solid volume and the fine aggregate content at 40% of mortar volume. Depending on the properties of mortar, the water to powder ratio is in the range of 0.9-1. This ratio should be carefully selected due to the high sensitivity of SCC to it. The self-compactability is achieved by adjusting the super- plasticiser dosage and the final water to powder ratio. This independent consideration of gravel and sand, results in a relatively high content of paste. The Japanese method has been adopted and used in many European countries as a starting point for the development of SCC (Brouwers and Radix, 2005).

Su and Miao (2003) then developed an alternative method, henceforth referred to as ‘the Chinese method’ which starts with packing all coarse and fine aggregates, and then filling of the aggregate voids with paste. This easier method can result in less paste and hence saving the most expensive constituents, namely cement and filler. With this method, concrete with normal strength is obtained, while in Japanese method a higher strength than actually required can be attained (Brouwers and Radix, 2005).

2.8 VMA-type SCC

By adding a high dosage of VMA to the mix of SCC, plastic viscosity can be controlled and increased without adding extra powder. To achieve flow-ability using this method a higher amount of super-plasticiser or higher water-powder ratio is required compared with the powder- type method.

2.9 Combined-type SCC

This type of mix was developed to improve the robustness of powder-type SCC by adding a small amount of VMA. In such mixes, the VMA content is less than that in the VMA-type SCC and the powder content and water to powder ratio are less than those in the powder-type SCC. The viscosity is provided by the VMA along with the powder. This type of SCC was reported to have high filling ability, high segregation resistance and improved robustness (Roziere et al., 2007).

2.10 Cement replacement materials (CRMs)

Stability and flow-ability are the main characteristics of SCC. They are achieved by limiting the coarse aggregate content, the maximum aggregate size and reducing water–powder ratios together with using super-plasticisers (SP) (Okamura et al., 1998). During the transportation and placement of SCC the increased flow-ability may cause segregation and bleeding which can be overcome by enhancing the viscosity of concrete mix, this is usually supplied by using a high volume fraction of paste, by limiting the maximum aggregate size or by using viscosity modifying admixtures (VMA) (Khayat, 1999). However, chemical admixtures are expensive and may contribute to increasing the cost of concrete. On the other hand, achieving high powder content by increasing the cement content is not feasible, and may lead to a significant rise in material cost and some negative impacts on concrete properties associated with the rise in temperature during hydration and higher drying shrinkage. Alternatively, incorporating cement replacement materials (CRMs) in concrete can impart many advantages to concrete through enhancement of particle distribution, cohesiveness, and reduction of the risk of thermal cracking as well as the improvement of certain mechanical and rheological properties

All CRMs have two common features; their particle size is smaller or the same as Portland cement particle and they become involved in the hydration reactions mainly because their ability to exhibit pozzolanic behaviour. By themselves, pozzolans which contain silica (SiO2) in a reactive form, have little or no cementitious value. However, in a finely divided form and in the presence of moisture they will chemically react with calcium hydroxide at ordinary temperatures to form cementitious compounds (Lewis et al., 2003; Domone and Illston, 2010). The most common CRMs used are ground granulated blast furnace (GGBS), micro-silica or silica fume (SF) and pulverised fuel ash or fly ash (FA).

2.9.1 Ground granulated blast-furnace slag (GGBS)

Ground granulated blast-furnace slag (Figure 2.8) is a by-product from the blast-furnaces used to make iron. It has been successfully used in many countries around the world achieving many technical benefits in construction industries (Uysal and Sumer, 2011; Boukendakdjia et al., 2012; Dinakar et al., 2013).

Adding GGBS to self-compacting concrete offers many advantages related to increasing its compactability, workability and retaining it for a longer time, while protecting cement against.

Figure 2.8: Ground granulated blast-furnace slag (GGBS)

Both sulphate and chloride attack (Russel, 1997). Because GGBS has 10% lower density than Portland cement, replacing an equal mass of cement by GGBS will result in a larger paste volume, which substantially increases the segregation resistance and flow-ability. Water demand tends to be less for concrete made with GGBS, owing to the smoother surface texture of the slag particles compared to cement, and to the delay in the chemical reaction (Lewis et al., 2003). Oner and Akyuz (2007), in their experiments on 32 different mixtures of SCC containing GGBS, indicated that as GGBS content increases, water-to-binder ratio decreases for the same workability and thus GGBS has a positive effect on the workability.

They proved further that the strength gain when using GGBS is more steady than concrete made with only cement with the same binder content. Although it tends to have lower strength at an early stage but as the curing period is extended (Figure 2.9), the strength increase was higher for the GGBS concretes. The reason is that the slow pozzolanic reaction and that the formation of calcium hydroxide requires time. Ramachandran et al. (1981) reported that depending on the desired properties, the amount of GGBS by the total mass of cementitious material content can be as high as 50 per cent. Oner and Akyuz (2007) indicated further that the compressive strength of concrete mixtures containing GGBS increases as the amount of GGBS increases. After an optimum point, at around 55% of the total binder content, the addition of GGBS does not improve the compressive strength (Figure 2.10), which can be explained by the presence of unreacted GGBS, acting as a filler material in the paste.

2.9.2 Micro-silica

The terms micro-silica, condensed silica fume, and silica fume are often used to describe by-products extracted from the exhaust gases of ferrosilicon, silicon, and other metal alloy smelting

furnaces. However, the terms of silica fume and micro-silica are used for those condensed silica fumes that are of high quality for use in the cement and concrete industry.

Micro-silica (Figure 2.11) consists primarily of amorphous (non-crystalline) silicon dioxide (SiO_2); when added to Portland cement concrete it improves its properties, in particular its compressive strength, bond strength, and abrasion resistance. The individual particles are extremely small, approximately 1/100th the size of an average cement particle. Because of its fine particles, large surface area, and the high SiO_2 content, silica fume is a very reactive pozzolan when used in concrete.

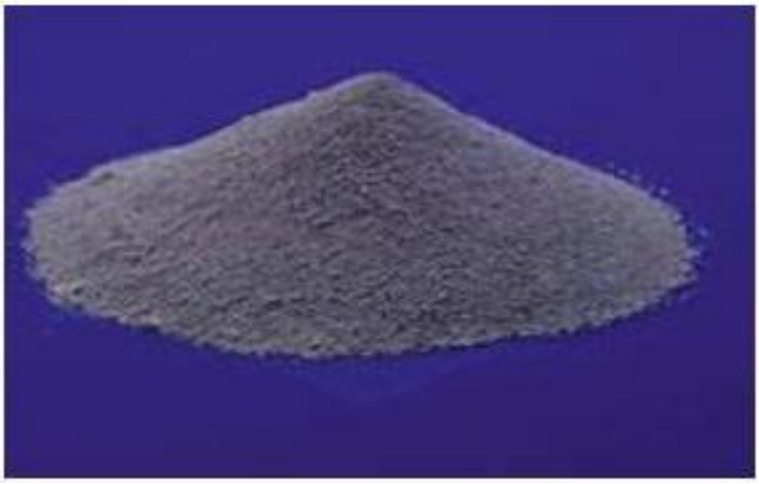


Figure 2.11: Micro-silica

Silica fume performs two roles in concrete (Siddique and Khan, 2011):

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 the spaces between grains.

Pozzolanic reaction: When Portland cement in concrete begins to react chemically, it releases calcium hydroxide (CH); these CH crystals 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 reacts with this CH to form additional binder material called Calcium Silicate Hydrate (C-S-H) which is very similar to the Calcium Silicate Hydrate formed from Portland cement and water and therefore reduces the CH content.

Fresh concrete containing silica fume is more cohesive and less prone to segregation and bleeding than concrete without silica fume. By studying the influence of silica fume on the workability, it is evident based on the results of Rao (2003) that the workability of mortar slightly decreases as the silica fume content is increased. This is due to the higher specific surface of silica fume, which needs more water for complete hydration and for workability.

Katkhuda et al. (2010) investigated 4 types of concrete M1, M2, M3, M4 with micro-silica content 0%, 10%, 15% and 20%, respectively. They observed a significant reduction in slump as the micro-silica content increases; their results were illustrated in Figure 2.12. The same was also been reported by Khayat and Guizani (1997) who revealed that the addition of small percentages of micro-silica, usually less than 10%, and of a proper amount of high range water reducing admixture (super-plasticiser) could decrease the viscosity of the paste, thus reducing the water demand and the risk of bleeding.

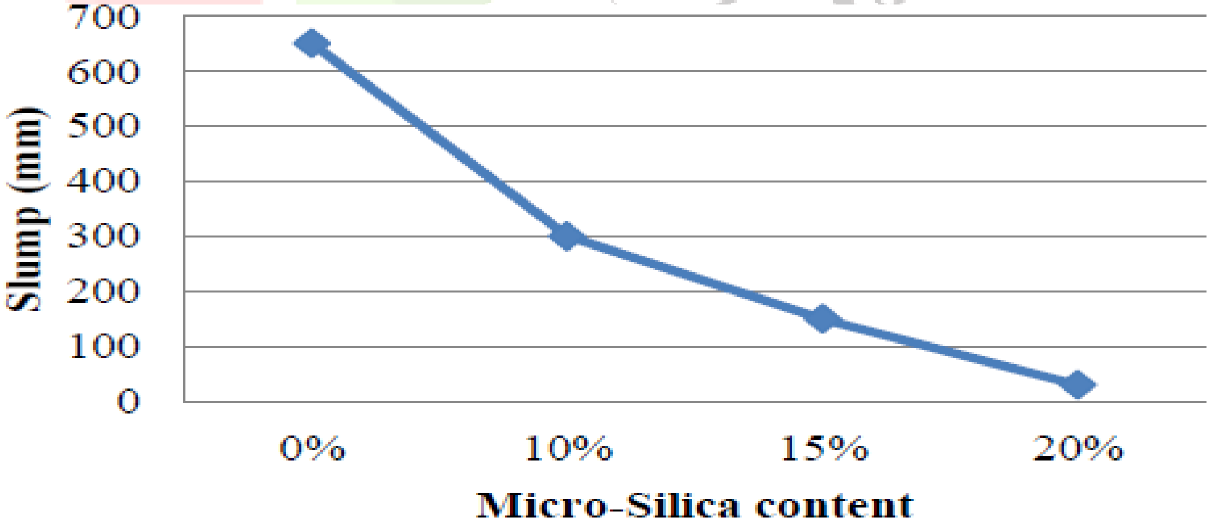


Figure 2.12: Reduction in slump as the micro-silica content increases

The addition of silica fume also reduces the permeability of concrete to chloride ions, which protects the reinforcing steel from corrosion, especially in chloride-rich environments such as coastal regions (Mazloom, et al., 2004).

Duval and Kadri (1998) studied the influence of micro-silica on the workability and compressive strength of concretes. It was found that micro-silica increased the compressive strength at most by 25%, but the workability of concretes was best when its content was between 4% and 8%. However, Duval and Kadri (1998) found out that if micro-silica exceeds 15% of the cementitious material, both compressive and tensile strengths are reduced.

Carlsward et al. (2003) also reported that micro-silica increases the yield stress of a SCC mix thus decreasing the slump flow and segregation. Vikan and Justnes (2003) also observed the same effect of micro-silica on the yield stress.

2.9.3 Fly ash (FA)

Fly ash (or pulverised fuel ash) is a by-product of coal-fired electricity generating plants. Because of its pozzolanic properties, fly ash (Figure 2.13) can be used as a partial replacement of Portland cement in SCC. The use of fly ash in SCC mixtures generally improves both its fresh and hardened properties. It can replace up to 30% by mass of Portland cement increasing the strength of SCC and its chemical resistance and durability. However, the maximum strength is reached more slowly than concretes made with only Portland cement. Due to its small spherical shape, adding FA to SCC mix can improve its workability while reducing water demand (Koehler et al., 2007). Bouzoubaa and Lachemib (2001) reported that the use of fly ash and GGBS in SCC reduces the amount of super-plasticiser needed to obtain slump flow spread as compared with concrete made with only Portland cement. Furthermore, Kim et al. (1996) studied the effect of fly ash on the workability of super-flowing concrete and reported that replacing 30% of cement with FA can result in excellent workability

Figure 2.13: Fly ash

FA increases the reactivity of SCC, leading to increased compressive strength, improved durability and reduced drying and autogenous shrinkage (Obla et al., 2003).

In terms of rheological properties, Sonebi (2004) reported that the use of fly ash reduced both the yield stress and plastic viscosity of SCC. However Park et al. (2005) found that fly ash slightly reduced yield stress but increased the plastic viscosity of super-plasticised pastes. Fly ash can also reduce bleeding and improve stability (Shadle and Somerville, 2002).

2.9.4 Using limestone powder in SCC

Fillers, such as limestone powder (Figure 2.14) are used as a portion of total CRMs to enhance certain properties of SCC. The use of limestone powder particularly in self-compacting concrete has been widespread in France and Sweden. Ground limestone is not a pozzolanic material and its action can be related to a change in the microstructure of the cement matrix associated with the small size of the particles, showing an enhancement in the packing density of powder, increasing the stability and the cohesiveness of fresh SCC and reducing the interstitial void thus decreasing entrapped water in the system.

Surabhi et al. (2009) reported that for a given water to binder ratio, replacing up to 20% of cement with limestone powder can enhance fresh and hardened properties of SCC. Figure 2.15 shows that replacing cement with 20% of limestone powder can increase the slump flow spread and can result in a moderate flow time t500. However, excessive amounts of fine particles can result in a considerable rise in the surface area of powder and an increase in inter-particle friction, due to solid-solid contact, which may affect the ability of the mixture to deform under its own weight, pass through obstacles and also a substantial rise in the viscosity (Yahia et al., 2005).

2.9.5 Effect of super-plasticiser (SP) on SCC

The hardened properties of self-compacting concrete are affected by its fresh behaviour which is dominated primarily by the dispersing of its components. With conventional concrete the cement particles group together to form flocs and therefore internal friction occurs within the mix, hindering its flow-ability as the particles will not be able to flow past each other with ease. Super-plasticisers or high-range water-reducing admixtures (HRWRAs) contribute to the achievement of denser packing and lower porosity in concrete by increasing the flow-ability and improving the hydration through greater dispersion of the cement particles, and thus assisting in producing SCCs of high strength and good durability.occurs within the mix, hindering its flow-ability as the particles will not be able to flow past each other with ease. Super-plasticisers or high-range water-reducing admixtures (HRWRAs) contribute to the achievement of denser packing and lower porosity in concrete by increasing the flow-ability and improving the hydration through greater dispersion of the cement particles, and thus assisting in producing SCCs of high strength and good durability.

Although SCC can be made with naphthalene sulfonate formaldehyde condensate (NSFC), melamine sulfonate formaldehyde condensate (MSFC), and lignosulfonate based HRWRAs (Assaad et al., 2003; Lachemi et al., 2003) but it is most commonly produced with

polycarboxylate-based HRWRAs. Polycarboxylate-based HRWRAs with its different structure and mode of action, represents an improvement over the other older sulfonate-based HRWRAs.

Sulfonate-based HRWRAs consist of anionic polymers that adsorb onto the cement particles and impart a negative charge, resulting in electrostatic repulsion.

Figure 2.16: Polycarboxylate-based super-plasticiser (left) and sulfanate-based super-plasticiser (right)

By contrast, polycarboxylate-based HRWRAs consist of flexible, comb-like polymers with a main polycarboxylic backbone and grafted polyethylene oxide side chains. The backbone, which includes ionic carboxylic or sulfonic groups, adsorbs onto a cement particle and the nonionic side chains extend outward from the cement particle. The side chains physically separate cement particles, which is referred to as steric hindrance as illustrated in Figure 2.19 (Koehler et al., 2007). Polycarboxylate-based HRWRAs may function by both electrostatic repulsion and steric hindrance (Bury and Christensen, 2002; Li et al., 2005) or only by steric hindrance (Blask and Honert, 2003; Li et al., 2005) depending on the structure of the polymer. Polycarboxylate-based super-plasticisers are more sensitive than sulfonate-based super-plasticiser to the amount of mixing energy (Koehler et al., 2007).

2.9.6 Viscosity modifying agents (VMA)

VMA, also known as anti-washout admixtures, can be added to the concrete mixtures to improve segregation resistance, cohesiveness and reduce bleeding. In general these admixtures increase yield stress and plastic viscosity. They may be also used as an alternative to increasing the powder content or reducing the water content of a concrete mixture (Koehler et al., 2007).

Acrylic- or cellulose- based water-soluble polymers or polysaccharides of microbial sources, such as welan gum are the commonly used viscosity-modifying agents in concrete. Water- soluble polymers can imbibe some of the free water in the system, thus increasing the viscosity of the cement paste which, in turn, enables the paste to hold aggregate particles in a stable suspension.

When using VMAs in SCC mixtures we should take into account its compatibility with the super-plasticiser used. For instance, cellulose derivatives are incompatible with a naphthalene- based super-plasticiser, whereas welan gum is compatible (Khayat, 1995).

Adding VMAs to SCC mixtures can alter cement hydration, resulting generally in a decrease in the compressive strength, flexural strength and modulus of elasticity of hardened concrete (Khayat, 1995).

2.9.7 Fibre reinforced self-compacting concrete

Cracks can be initiated in concrete at three main areas:

‘The interfacial transition zone’ which represents the interface between aggregates and mortar in concrete;

- In the cement paste or mortar matrix;
- In the particles of aggregates.

The point where the crack can be initiated will depend on the relative strengths of these three phases.

Coarse aggregates increase the toughness of concrete mix. However, the presence of sharp particles in a mix relatively close to each other can prevent the easy flow of SCC. Due to this reason, coarse aggregate content need to be reduced in SCC mixes. However, one of the major drawbacks in doing so is the brittle nature of the mix. This is because all the energy that was previously consumed by micro-cracking, debonding and crack coalescence is now available for the propagation of pre-existing cracks in the material.

Inherently, self-compacting concrete is a brittle material with low strain capacity under tensile loading. By adding randomly oriented discrete fibres, the performance (strength and toughness) of SCC can be improved and concerns related to SCC brittleness and poor resistance to crack growth addressed by preventing or controlling initiation, propagation or coalescence of cracks (Sahmaran et al., 2005).

The concept of using fibres as reinforcement is not new. Fibres have been used as reinforcement since ancient times. They have been produced from a wide range of materials, shapes and characteristics (Figure 2.20); glass (Ferreira and Branco, 2007), PVA (Poly Vinyl Alcohol) (Bezerra et al., 2004), polypropylene (Richardson and Dave, 2008), carbon (Bayasi and Kaiser, 2003), Asbestos (Murali et al., 2012) and steel fibres (Benson and Karihaloo, 2005a)...etc.

The characteristics and performance of fibre reinforced concrete depend on the properties of concrete and the fibres. The properties of fibres that are usually of interest are fibre volume fraction Vf, fibre geometry (fibre length Lf /fibre diameter df), fibre orientation, and fibre distribution. Fibre length and volume fraction are selected based on the maximum aggregate size used. It is recommended to choose fibres not shorter than the maximum aggregate size (Vandewalle, 1993; Johnston, 1996).

Usually, the fibre length is 2-4 times that of the maximum aggregate size (Grünewald and Walraven, 2009). Johnston (1996) indicates that the maximum coarse aggregate size is important because the number of rigid straight fibres like steel that can be accommodated within a unit volume reduces with an increase in the maximum aggregate size as shown schematically in Figure 2.21.

Testing self-compacting concrete

Assessing the workability of SCC mix can be divided into three categories as proposed by Tattersall (1991):

Qualitative assessment; it is a general description of concrete behaviour such as workability, flow-ability, stability, compactability, pump-ability…etc. without any attempt to quantify. This was discussed previously in this Chapter.

Quantitative empirical assessment to be used as a simple description of quantitative

- behaviour such as slump flow test, L-box test…etc.
- Quantitative fundamental assessment; it is a description related to rheological terms of concrete, e.g. plastic viscosity, fluidity and yield value.

For SCC mix, the quantitative fundamental rheological tests can be performed using rheometers of different types. However, these tests suffer for some drawbacks; they are not suited for use at the working site, and they can be rather time-consuming (Utsi et al., 2003). Therefore, it is important to find suitable workability test methods for continuous use outside the laboratory, and to calibrate them with the rheological parameters. For the SCC mix, a number of quantitative empirical workability assessment tests have been proposed and established in practice, such as slump flow test, J-ring test, L-box test, V-funnel test, U-box test and wet sieve stability…etc. In this section, the workability tests which are recommended by the British standard (BS EN 206-9, 2010) are discussed, namely the slump flow test for flowing ability, L-box and J-ring tests for passing ability, and visual inspection or sieve stability test can be used for segregation resistance

Flow-ability using slump test

The slump test with its simple and rapid procedure is used to evaluate the deformability of SCC in the absence of obstacles. This test measures two different aspects; the filling ability by measuring the horizontal flow diameter SF and the viscosity of mix by measuring the time needed for SCC to reach 500 mm flow (t500). The segregation resistance in this test can be detected visually. Because of its simplicity, the slump test can be done either on site or in the laboratory with inverted or upright Abram’s cone.

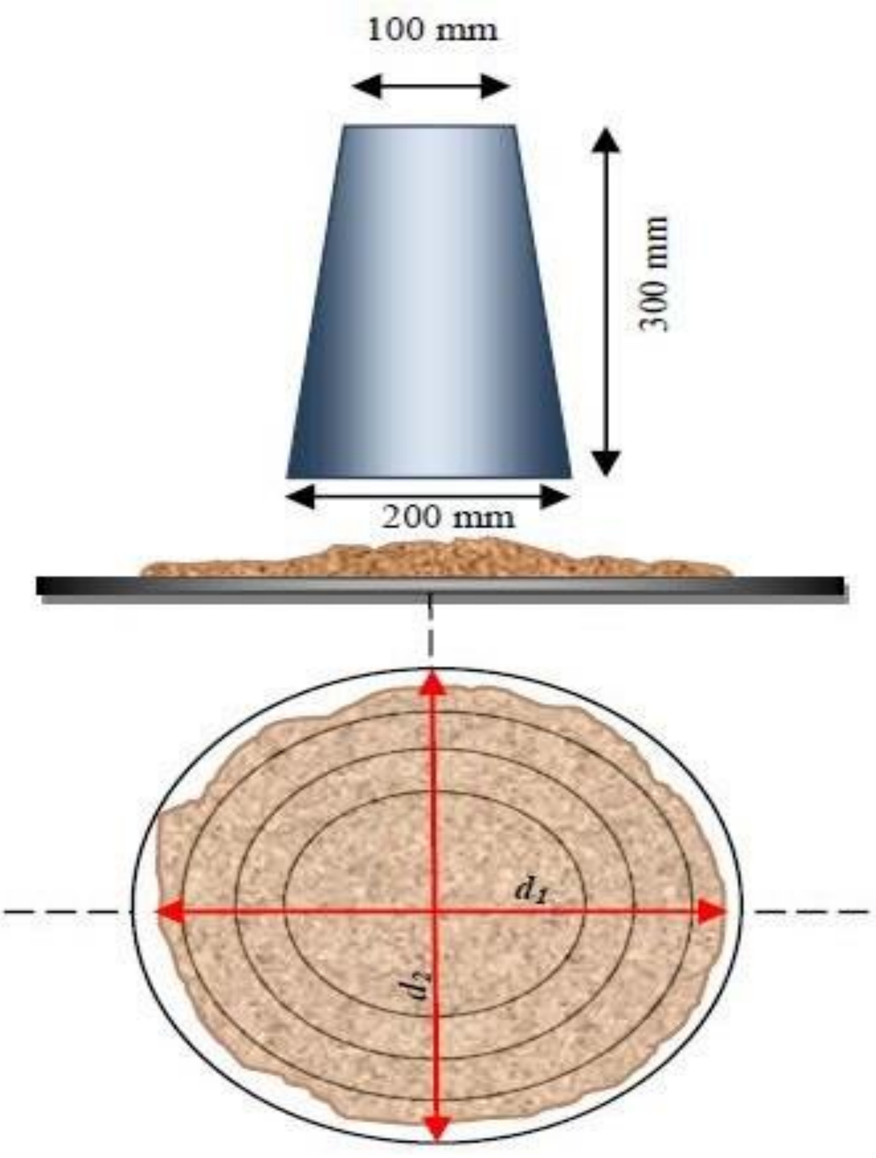


Figure 2.24: Slump test apparatus with upright cone

The cone is placed on a non-absorbing levelled flat steel surface with a plane area of at least 900 mm x 900 mm, filled with SCC, and lifted in 2 to 4 sec to a height of 15 to 30 mm; SCC flows out under the influence of gravity. Two horizontal perpendicular diameters d1 and d2 as illustrated in Figure 2.24 are recorded and the average flow spread diameter SF is calculated using Equation (2.1)

$$SF = \frac{(d_1 + d_2)}{2}$$

Criteria of acceptance (BS EN 12350-8, 2010)

- Achieving a large diameter with no segregation indicates a good deformability and a low yield stress.t500 ‘the time needed for SCC to reach a diameter of 500 mm’ should be recorded.
- This test is not acceptable when the largest aggregate size in more than 40 mm.
- The difference between d1 and d2 should be less than 50 mm otherwise the test should be repeated.
- Segregation can be detected by visually inspecting a ring of cement paste/mortar in the edge of flow, and /or ensuring that no coarse aggregates and fibres have lifted in the centre of flow.
- According to the latest mix design guidelines for self-compacting concretes (BS EN 206-9, 2010) two viscosity classes are introduced: viscosity class 1 (VS1) and viscosity class 2 (VS2) depending on whether t500 < 2 sec or ≥ 2 sec.

2.14.1 Passing ability tests

2.14.1.2 J-ring test

J-ring is a test used in conjunction with a slump test to assess the passing ability of SCC with or without fibres through gaps in the obstacles, e.g. reinforcement. For this test, the slump test apparatus is used with an open steel rectangular section ring with 16 steel rods (ϕ16 mm) and 100 mm height, as shown in the Figure 2. 25. The gap between the bars is 42 mm . Wider gaps can be used when fibres are introduced to the mix which should be 1-3 times the maximum length of fibres used (Tviksta, 2000).

After filling the cone with concrete without using any vibration or rodding, the cone is lifted perpendicular to the steel base plate allowing the concrete to flow freely. The time needed for the flow to reach 500 mm diameter is recorded as t500J, and the flow allowed to stop before recording the remaining measurements.

Flow spread of the J-ring (SFJ) indicates the restricted deformability of SCC and can be expressed using Equation (2.2)

$$SF_J = \frac{(d_1 + d_2)}{2} \tag{2.2}$$

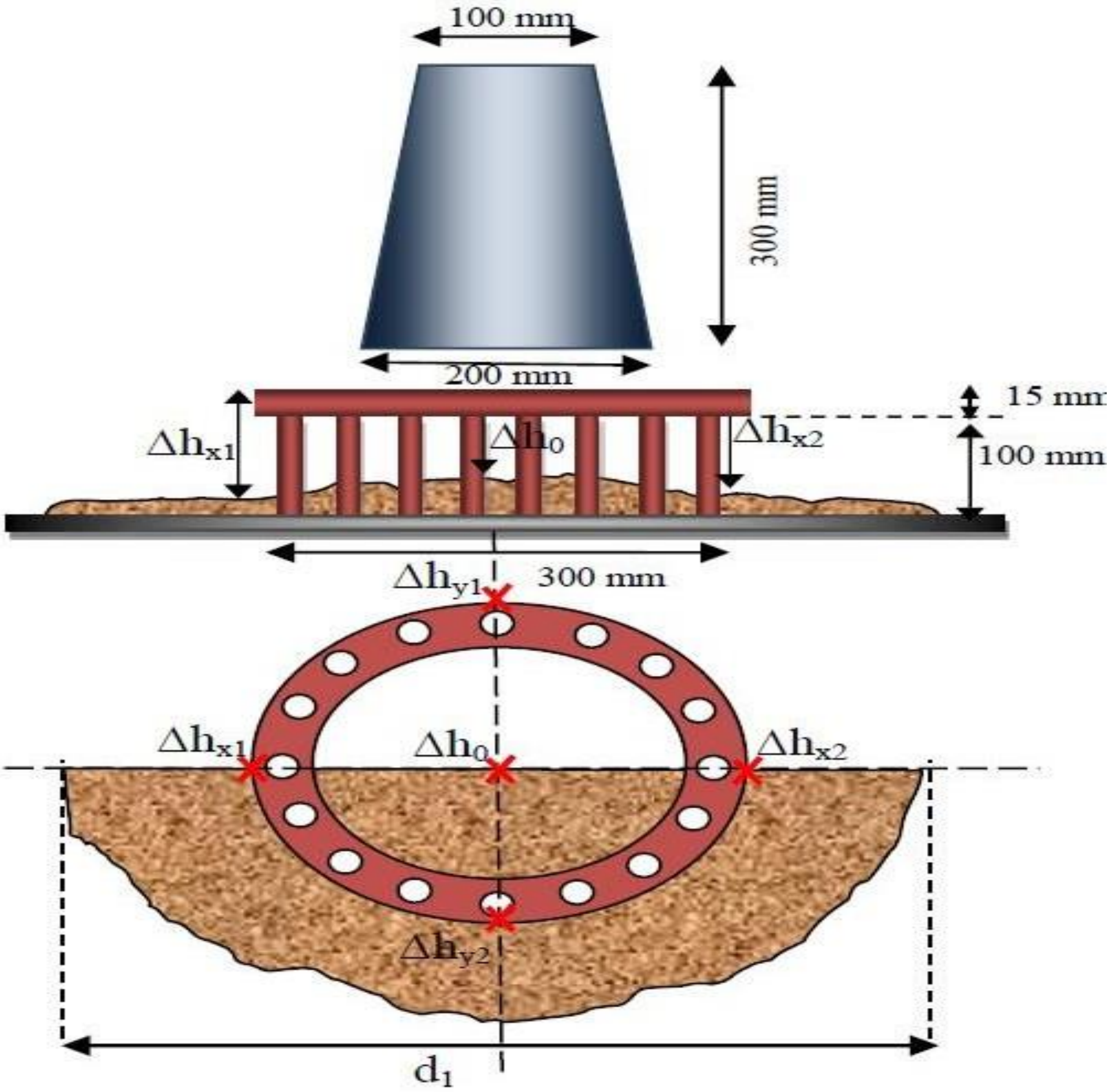


Figure 2.25: J-ring test apparatus

Flow time t500J has been recorded.

Blocking step PJ is calculated using Equation (2.3).

$$P_J = \frac{\Delta h_{x1} + \Delta h_{x2} + \Delta h_{y1} + \Delta h_{y2}}{4} - \Delta h_0 \qquad (2.3)$$

where:

Δh0: is the height measurement at the centre of flow.

Δhx1, Δhx2, Δhy1, Δhy2 are the four measurement heights at positions just outside the J-ring.

Criteria of acceptance

According to (Chan et al., 2010), the flow spread (SFJ) of SCC, with or without steel fibres using the J-ring can be assessed relative to the flow spread (SF) of the same mix using the slump test as described in Table 2.1

Table 2.1. Passing ability criteria

(SF-SF_J)	Passing ability rate	Notes
< 25 mm	0	No visible blocking
25 mm - 50 mm	1	Minimal to noticeable blocking
> 50 mm	2	Noticeable to extreme blocking

The blocking step PJ should be less than 10 mm based on EFNRC. T500J which is the time needed for SCC to reach a diameter of 500 mm should be recorded.

- This test is not acceptable when the largest aggregate size in more than 40mm.
- The difference between *d*1 and *d*2 should be less than 50 mm otherwise the test should be repeated.
- Segregation can be detected by visually inspecting a ring of cement paste/mortar in the edge of flow, and /or ensuring that no coarse aggregates or fibres have lifted in the centre.

2.14.1.3 L-box test

The L-box test is used to assess the filling and passing ability of SCC, or in other words the ability of concrete to pass though reinforced bars without blocking or segregation. After filling the vertical column of the L-box, the gate is lifted to allow SCC to flow into the horizontal part after passing through the rebar obstructions. Two measurements are taken, (H1, H2) heights of concrete at the beginning and end of the horizontal section, respectively. The ratio H2/H1 represents the filling ability, and typically, this value should be 0.8~1, while the passing ability can be detected visually by inspecting the area around the rebar.

In L-box, 2 or 3 smooth steel bars with 12 mm diameter can be used to represent light or dense reinforcement with distance between them 59 and 41 mm, respectively.

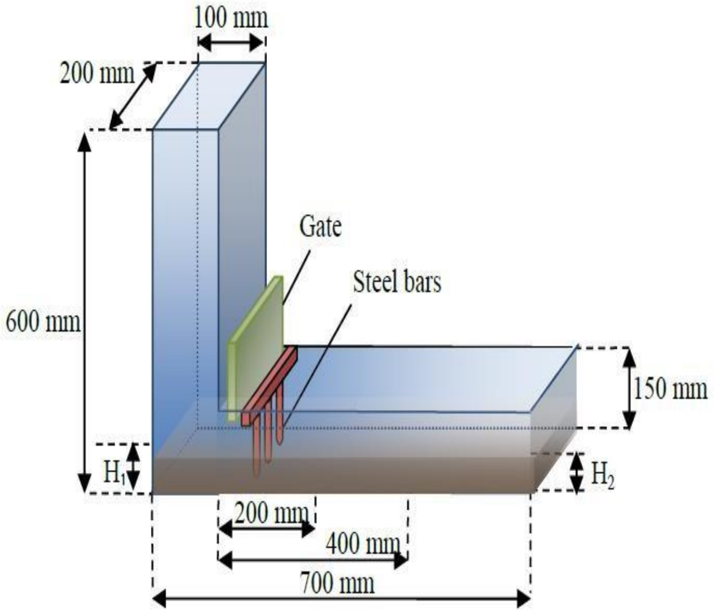


Figure 2.26: L-box test apparatus

The passing ability ratio PL should be calculated:

$$PL = \frac{H_2}{H_1}$$

Where -

H1 is the mean depth of concrete in the vertical section of the box

H2 is the mean depth of concrete at the end of the horizontal section of the box.

t200 and t400 are also recorded which represent the time of SCC to reach 200 mm and 400 mm from the gate, respectively as illustrated in Figure 2.26.

Criteria of acceptance

- For this test, at least 14l of SCC should be prepared in accordance with (BS EN 12350- 10, 2010).
- No signs of segregation or bleeding.
- Passing ability ratio PL should be between 0.8 and 1; a value more than 1 means an error. There is no recommendation for t200 and t400 values, but larger values represent higher

It should be mentioned that this test is very sensitive to the operators in terms of the speed of lifting the gate. Slow lifting could result in an increase in t200 and t400.

2.14.2 Segregation resistance tests

Several empirical tests have been proposed to evaluate SCC segregation.

2.14.3 Visual examination

The visual examination method is carried out by inspecting the periphery of the concrete after measuring the slump flow spread and rating it from 0 to 3 (PCI, 2003). However it is an inadequate method because it relies on the experience of the individual and fails to evaluate segregation quantitatively.

2.14.3.1 Sieve stability test

The potential for static segregation can be evaluated by a simple sieve stability test, which measures the amount of grains passing through a 5 mm sieve after a standard period, which is called sieve segregation or segregation index. In this test, 10 litres of fresh SCC are placed into a test container and allowed to settle over a 15 minute period. The coarse aggregate settles at the bottom and the upper part of the concrete in the container is then wet sieved and the volume of mortar calculated. The more the segregation has occurred the more mortar passes through the sieve, indicating a higher risk of segregation after the placement of SCC.

2.16 SCC applications

Following its success in Japan with more than 400,000 m3 of annual production for bridges and buildings, other parts of the world have embraced SCC.

- At over 828 meters (2,716.5 ft) and 166 stories, Burj Khalifa (2010) in Dubai (Figure 2.31) holds the record of the tallest building and free standing structure in the world with the largest number of stories. Self-compacting concrete is playing a greater role in high-rise construction to overcome the problem of congested reinforcement and ease of placement. The groundwater in which the Burj Dubai substructure is constructed is particularly severe, with chloride concentrations of up to 4.5%, and sulfate of up to 0.6%. The chloride and sulfate concentrations found in the groundwater are even higher than the concentrations in seawater. Accordingly, the primary consideration in designing the piles and raft foundation was durability. The concrete mix for the piles which are 1.5 m in diameter and 43 m long with design capacity of 3000 tonnes each was a 60 MPa mix based on a triple blend with 25% fly ash, 7% silica fume, and a water to cement ratio of 0.32. A viscosity modifying admixture was used to obtain a slump flow of 675 +/- 75 mm to limit the possibility of defects during construction.

- The 800 million dollar Sodra Lanken (1997) Project in Sweden (Figure 2.32) notably was one of the largest infrastructure projects that used SCC. The six kilometres long four-lane highway in Stockholm involved seven major junctions, and rock tunnels totalling over 16 km partly lined with concrete and over 225,000 cubic meters of concrete. Incorporating

Figure 2.31: Burj Khalifa in Dubai

Figure 2.32: The Sodra Lanken Project links east and west of Stockholm's southern side

SCC was ideal to cope with the density of reinforcement required and the highly uneven rock surfaces

Chapter 3

Development of self-compacting concrete mixes

3. 1 Introduction

The ideal design of a self-compacting concrete (SCC) mix is a compromise between two conflicting objectives. On the one hand, the SCC has to be as fluid as possible to ensure that it will fill the formwork under its own weight, but on the other, it has to be a stable mixture to prevent segregation of solids during the flow (Su et al., 2004; Roussel, 2007; Spangenberg et al., 2010). The former is ensured by using super-plasticiser and/or viscosity modifying admixtures, while the latter is achieved through the selection of the right amount and type of powders i.e. cement and cement replacement materials (CRM) and by striking the right balance between the solids and liquids in the mix.

The addition of steel fibres improves the mechanical properties and the ductility of SCC in much the same manner as in vibrated concrete. However, the fibres greatly impair the workability of SCC because of their elongated shape and large surface area. The amount of fibre that can be added to a SCC mix is therefore limited and depends on the fibre type used and the composition of the SCC mix. The maximum amount of fibre needs to be determined in such a way as to cause the least decrease in the workability, whilst maintaining good flow and passing ability. In order to make the best use of the fibres, they need to be homogeneously distributed in the mix without clustering (Grünewald and Walraven, 2003).

This Chapter describes the steps taken to develop self-compacting concrete (SCC) mixes of varying strengths and performance, with and without steel fibres. The aim is to investigate how the proportions of solids and liquids, the amount of super-plasticiser, and the steel fibres need to be selected in order to produce SCC mixes with the right flow and passing ability. For the self-compacting concrete mixes without steel fibres the fulfilment of the flow and cohesiveness criteria are sufficient for the mix design. However, for the design of self-compacting concrete mixes with steel fibres, they must additionally meet the passing ability criterion.

The plastic viscosity of the SCC mixes so developed will then be estimated by the micromechanical procedure described by (Ghanbari and Karihaloo, 2009). This plastic viscosity,

together with the yield stress of the mix, is needed in the numerical simulation of SCC flow in moulds of different shapes and sizes.

The first part of this chapter has been published in the journal 'Magazine of Concrete Research' (see publication 4 in the list in Chapter 1), while the second part of this Chapter has been published in the journal 'Cement and Concrete Composites' (see publication 2 in the list in Chapter 1).

Experimental program flow-chart

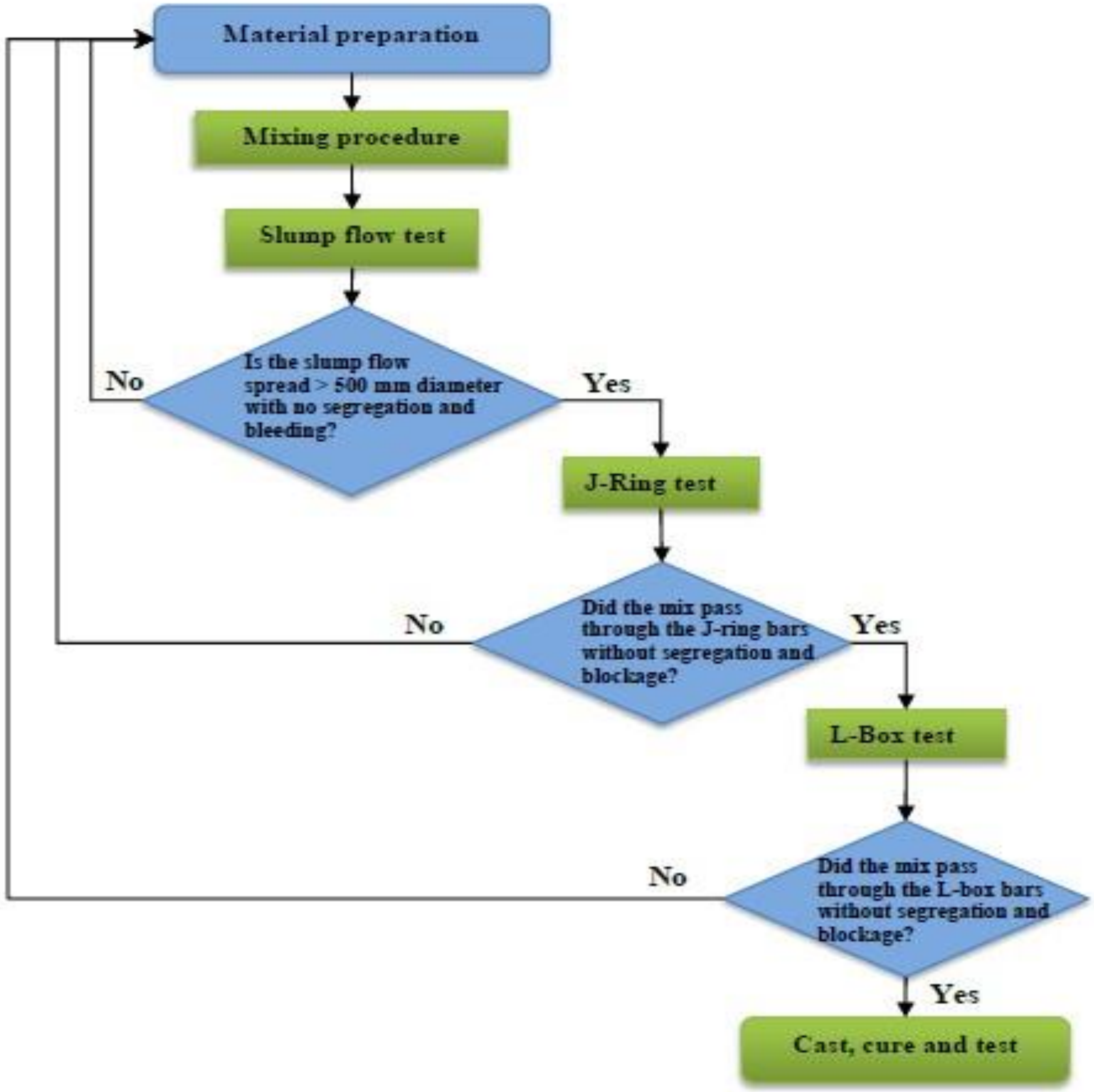


Figure 3.1: Experimental program flow chart

Table1- Proportion of concrete mix-

Mix No.	Group	Cement Type	Filler %	Coarse Agg.	Cement Kg/m3	Coarse Kg/m^3	Sand Kg/m^3	Filler Kg/m^3	Water Kg/m^3	Adm. Kg/m^3
1	**Gravel**	OPC	-	0.67	350	1267.5	624.3	0	140	7.9
2		OPC	LF 10	0.45	400	776.7	949.3	40	160	9
3		OPC	LF 20	0.45	400	758.7	927.3	80	160	9
4		OPC	LF 30	0.45	400	740.7	905.3	120	160	9
5		OPC	SF 10	0.45	350	821.6	1004.2	35	140	7.9
6		OPC	SF 10	0.45	400	776.7	949.3	40	160	9
7		OPC	SF 10	0.55	400	932.0	793.9	40	160	9
8		OPC	SF 10	0.45	450	731.7	894.4	45	180	10.1
9		OPC	SF 10	0.55	450	878.1	748.0	45	180	10.1
10		HSPC	SF 10	0.45	350	821.6	1004.2	35	140	7.9
11		HSPC	SF 10	0.45	400	776.7	949.3	40	160	9
12	**Dolomite**	OPC	-	0.67	350	1267.5	624.3	0	140	7.9
13		HSPC	LF 10	0.45	400	776.7	949.3	40	160	9
14		HSPC	LF 20	0.45	400	758.7	927.3	80	160	9
15		HSPC	LF 30	0.45	400	740.7	905.3	120	160	9
16		OPC	LF 10	0.45	400	776.7	949.3	40	160	9
17		OPC	SF 10	0.45	400	776.7	949.3	40	160	9
18		OPC	SF 10	0.55	400	932.0	793.9	40	160	9
19		HSPC	SF 10	0.45	400	776.7	949.3	40	160	9

Specimen preparation and testing

The dry materials required for each batch were weighted and mixed using a mechanical concrete mixer. The water in addition to admixture and cement or cement- filler was mixed for a half minute to ensure the uniformity of the constituents. Sand was simultaneously charged into the mixer and was mixed for a half minute and then coarse aggregate was added and mixing at least for two minutes. Slump test was carried out according to the British standard specification to control the consistency of the fresh mixes for normal compacting concrete NC. Fresh concrete for self compacting concrete SCC was subjected to evaluate the slump flow (flowability), passingability and segregation potential. Slump flow test, V funnel test, U box test and L box test was carried out according to[9-11] to control the consistency and workability of the fresh mixes of SCC. Standard slump cone (200mm by 100mm by300mm) was filled with concrete and required both time (T50cm) take for concrete to reach a500mm slump flow diameter and the mean diameter D of the spread lifting the cone. VFunnel test was used to determine the segregation potential. The bottom opening has the dimension of 75mm by 75mm to a depth of150mm. The funnel is filled with concrete and time T taken for the concrete to leave the funnel is measured. Then, the funnel is refilled with the same concrete and allowed to settle for 5 minutes. The new time T5min required for the concrete to leave the funnel is measured. The difference in time is a measure of segregation resistance of the concrete mix.

The L box test is another test method, in which the vertical part is first filled with concrete then a hatch is removed and concrete flows out between rebar. The height level of the concrete on each side H1 and H2 of the L box are measured and calculate H2/H1. Moreover, in U box, the left hand section is filled with concrete and then lifted the gate and concrete flow upwards into the other section. After the upwards into the other section. After the concrete has come to rest required the height in two places H1 and H2 and calculate (H1-H2).

Standard cubes (15x15x15cm) of concrete mix were prepared to measure compressive and tensile splitting strength. Standard beams(10x10x50cm) were prepared to measure flexural strength and impact strength. Figure 5 shows the test apparatus for the impact test. A hydraulic compression testing machine of total capacity 15oo kN was used for compression and splitting test, while, the Universal testing machine of total capacity 300 kN was used for flexural test.

Moreover, the influence of exposure to fire after 28 days in compressive strength was investigated on cubes l5xl5xl5cm. The concrete cubes were put on fire chamber at 400 °C for two hours and left in laboratory temperature up to cold, after then the specimens applied to compressive test. Comparative study for corrosion resistance of concrete specimens "lollipop" of 10cm diameter and 20cm height concrete cylinder in which steel reinforcement bars 10mm diameter and35cm length were imbedded in concrete cylinder. Each steel reinforcement bar was weighted firstly and embedded to 15cm length in concrete cylinder keeping 20cm over length out of the cylinder. An accelerated test for corrosion was applied by using power supply at constant current and switch to maximum voltage. Stainless steel bar with 10mm diameter was used as a cathode and the steel bar act as the anode. The lollipop specimens was cured in water, 20 °C, for 14 days and then immerged in fiber glass container to half depth in 5% NaCl solution at age of 14 days to still to another 14 days in the solution, Figure 6 shows the accelerated corrosion cell. After then the specimens leave the container and the steel reinforcement pull out from cylinder by pull out test using the hydraulic testing machine of total capacity 300 kN or crushing the concrete cylinder and then cleaned carefully to cut the rust from the steel, the steel reinforcement weighted and calculate the percent of weigh loss W.

Table 3- **Test result of fresh concrete mixes-**

Mix No.	Group	Cement Type	Filler %	Coarse Agg.	Cement Kg/m3	Slump Flow		V Funnel		U Box	L Box
						T50	D	T0	T5min	H2/H1	H2/H1
1	**Gravel**	OPC	-	0.67	350	-	-	-	-	-	-
2		OPC	LF 10	0.45	400	3	650	7	10	10	1
3		OPC	LF 20	0.45	400	4	650	9	11	10	1
4		OPC	LF 30	0.45	400	5	670	11	12	20	0.85
5		OPC	SF 10	0.45	350	4	650	7	10	20	0.85
6		OPC	SF 10	0.45	400	3	650	5	7	10	1
7		OPC	SF 10	0.55	400	2	650	5	8	0.0	1
8		OPC	SF 10	0.45	450	2	750	4	6	0.0	1
9		OPC	SF 10	0.55	450	2	800	4	7	0.0	1
10		HSPC	SF 10	0.45	350	4	650	6	9	3.0	0.8
11		HSPC	SF 10	0.45	400	3	650	5	7	20	1
12	**Dolomite**	OPC	-	0.67	350	-	-	-	-	-	-
13		HSPC	LF 10	0.45	400	4	650	9	11	30	1
14		HSPC	LF 20	0.45	400	4	650	11	13	40	1
15		HSPC	LF 30	0.45	400	5	650	12	15	45	0.8
16		OPC	LF 10	0.45	400	4	650	10	13	30	1
17		OPC	SF 10	0.45	400	3	700	6	9	20	1
18		OPC	SF 10	0.55	400	2	700	6	9	10	1
19		HSPC	SF 10	0.45	400	3	650	6	9	15	1

Fresh concrete

The use of gravel recorded more workability with less homogeneous for self compacted concrete than dolomite according to the test measured in this work. The flowability, passingability and segregation resistance of SCC measured by slump flow, V funnel, U box and L box test. Dolomite is recommended than gravel to enhance the workability problems and maintain the homogenous of SCC. Increase in cement content decrease the flow time and increase the passigability by U and L box, and the use of HSPC recorded the same trained of OPC. The increase in coarse aggregate content from0.45 to 0.55 decrease the flow time while the segregation resistance decreases by about 12.5% measured by V funnel T5min (mix 7 compared with mix 6, content 400 kg/m3 cement) and by 14.3 % (mix 9 compared with mix 8, content 450 kg/m3 cement), this results recorded for more flowable mix cast with gravel. The deference between SF and LF filler up to 10% addition of cement weight not remarkable. These results go to use the lime stone filler as use silica fume. On the other hand, the increase in lime stone filler resulted in reduction in flowability of mixes and with regard to mixes cast with gravel the flow time for mix 2, mix 3 and mix 4 were 3, 4 and 5 sec., for 10 %, 20 % and 30 % addition lime stone filler by cement weight OPC, respectively. While, the flow time for mix 13, mix 14 and mix 15 were 4, 4 and 5 sec., for 10 %, 20 % and 30 % lime stone filler addition of cement weight HSPC, and using dolomite, respectively.

Table 4 – Test result of Mechanical Properties of concrete-

Mix No.	Group	Cement Type	Filler %	Coarse Agg.	Cement Kg/m3	Compressive Strength MPa		Flexural Strength MPa	Impact Strength No. of Blows
						14	28	28	28
1	Gravel	OPC	-	0.67	350	22	26	6	5
2		OPC	LF 10	0.45	400	25	27.5	4.8	3
3		OPC	LF 20	0.45	400	24	29	5.8	4
4		OPC	LF 30	0.45	400	28	30	5.3	4
5		OPC	SF 10	0.45	350	23	25	4.8	4
6		OPC	SF 10	0.45	400	25	28	5	4
7		OPC	SF 10	0.55	400	31.5	36	5.8	4
8		OPC	SF 10	0.45	450	34	39.5	6.5	17
9		OPC	SF 10	0.55	450	33	37	7.3	3
10		HSPC	SF 10	0.45	350	22	28	5	3
11		HSPC	SF 10	0.45	400	29	32	5.3	7
12	Dolomite	OPC	-	0.67	350	25	30	6.5	5
13		HSPC	LF 10	0.45	400	29	35.5	7.5	8
14		HSPC	LF 20	0.45	400	26	37.5	7.3	7
15		HSPC	LF 30	0.45	400	32.5	33	7	5
16		OPC	LF 10	0.45	400	28.5	35.5	7.8	5
17		OPC	SF 10	0.45	400	25	32.5	7	5
18		OPC	SF 10	0.55	400	38.5	42	7.8	6
19		HSPC	SF 10	0.45	400	33.5	38	7.3	10

TABLE 5:- Effect of using SCC on Mechanical Properties-

Mix No.	Group	Cement Type	Filler %	Coarse Agg.	Cement Kg/m3	Compressive Strength MPa		Flexural Strength MPa	Impact Strength No. of Blows
						14	28	28	28
1	Gravel	OPC	-	0.67	350	22	26	6	5
2		OPC	LF 10	0.45	400	25	27.5	4.8	3
3		OPC	LF 20	0.45	400	24	29	5.8	4
4		OPC	LF 30	0.45	400	28	30	5.3	4
5		OPC	SF 10	0.45	350	23	25	4.8	4
6		OPC	SF 10	0.45	400	25	28	5	4
7		OPC	SF 10	0.55	400	31.5	36	5.8	4
8		OPC	SF 10	0.45	450	34	39.5	6.5	17
9		OPC	SF 10	0.55	450	33	37	7.3	3
10		HSPC	SF 10	0.45	350	22	28	5	3
11		HSPC	SF 10	0.45	400	29	32	5.3	7
12	Dolomite	OPC	-	0.67	350	25	30	6.5	5
13		HSPC	LF 10	0.45	400	29	35.5	7.5	8
14		HSPC	LF 20	0.45	400	26	37.5	7.3	7
15		HSPC	LF 30	0.45	400	32.5	33	7	5
16		OPC	LF 10	0.45	400	28.5	35.5	7.8	5
17		OPC	SF 10	0.45	400	25	32.5	7	5
18		OPC	SF 10	0.55	400	38.5	42	7.8	6
19		HSPC	SF 10	0.45	400	33.5	38	7.3	10

3. 3 Development of SCC base mixes with and without fibres

3.3.1 Self-compacting normal and high-strength concrete

An extensive laboratory investigation was conducted to produce different grades of self-compacting normal and high-strength concrete mixes (with nominal 28 day cube characteristic compressive strengths of 35 MPa, 45 MPa, 60 MPa, 80 MPa and 100 MPa) that on one hand were as fluid as possible to ensure that they filled the formwork under their own weight, passed through congested reinforcement cages without blockage, and on the other were stable to prevent segregation of solids during the flow. This investigation followed the traditional trial and error approach, using the slump cone test, J-ring test and L-box test on trial mixes, until the mix that met the flow-ability and passing ability criteria and had no visible signs of segregation according to the Code (BS EN 206-9, 2010) was found.

Although the mix proportions of vibrated mixes of the same compressive strength made in the same laboratory are available, we shall use only two of those vibrated mixes (40 MPa and 100 MPa vibrated mixes) to develop the full range of SCC mixes. However, later we shall compare the SCC mixes so developed with the corresponding vibrated mixes.

3.3.1.1 Mix preparation

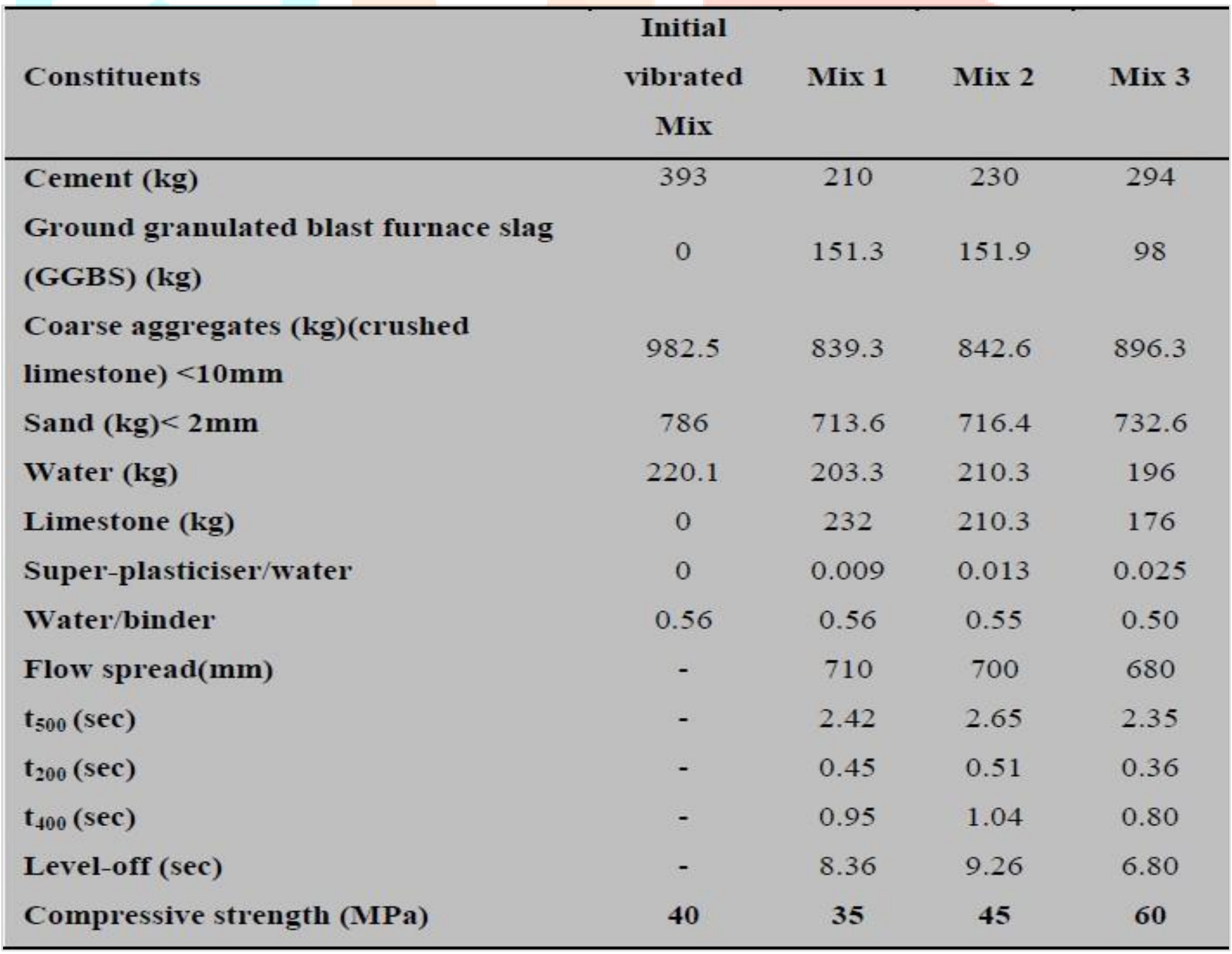
The trial mixes were prepared in a planetary mixer by mixing the coarsest constituent (coarse aggregate) and the finest one (GGBS and/or micro-silica), followed by the next coarsest (sand) and next finest constituent (cement), and so on. Before each addition, the constituents were mixed for 2 minutes. To fluidize the dry mix, two-thirds of the super-plasticiser (SP) was added to the water. One-half of this water-SP mixture was added to the dry constituents and mixed for two minutes. One-half of the remaining water-SP mixture was then added and mixed for two minutes. This process was continued until all water-SP mixture was added. The remaining one- third of the SP was added and mixed for two minutes just before transferring the SCC mix into the slump cone. The horizontal spread up to 500 mm was timed. If any segregation was visible, the mix proportions were judiciously altered. This trial process was continued until the mix met the flow-ability criterion (BS EN 206-9, 2010) and was homogeneous with no visible segregation or bleeding. In this manner, all self-compacting normal and high-strength concrete mixes were developed. The mix proportions of these mixes are shown in Table 3.1 and Table 3.2 below. The binder refers to cement plus GGBS and /or micro-silica.

3.3.1.2 Normal strength concrete

The trial mixes for normal strength concrete with 28-day cube compressive strengths of 35, 45 and 60 MPa (mixes 1, 2, and 3 in Table 3.1) were proportioned guided by the corresponding 40 MPa vibrated concrete mix proportions produced in the same laboratory and by the ad hoc guidance available in the literature (Chapter 2). Part of the cement was replaced by the lighter granulated ground blast furnace slag (GGBS) to increase the paste volume and lubricate the aggregate particles. For the same reason limestone powder (particle size range 0.05-2 mm) was added to all SCC mixes. The water to binder ratio was reduced from 0.56 for the 35 MPa mix to

0.5 for the 60 MPa, whereas the super-plasticiser to water ratio was increased from 0.009 for the 35 MPa mix to 0.025 for the 60 MPa SCC mix. The sand (particle size range 0.15-2 mm) content was slightly decreased (by 6% to 9%) in the SCC mixes in comparison with the corresponding vibrated mixes. The coarse aggregate (crushed limestone without dust, particle size range 4-10 mm), content was decreased by 8% for the 60 MPa mix to 14% for the 35 MPa mix in comparison with the vibrated mix, in order to reduce the inter-particle friction.

The mix proportions of the initial vibrated concrete mix and the normal strength SCC mixes (Mix 1, Mix 2 and Mix 3) are reported in Table 3.1.



Constituents	Initial vibrated Mix	Mix 1	Mix 2	Mix 3
Cement (kg)	393	210	230	294
Ground granulated blast furnace slag (GGBS) (kg)	0	151.3	151.9	98
Coarse aggregates (kg)(crushed limestone) <10mm	982.5	839.3	842.6	896.3
Sand (kg)< 2mm	786	713.6	716.4	732.6
Water (kg)	220.1	203.3	210.3	196
Limestone (kg)	0	232	210.3	176
Super-plasticiser/water	0	0.009	0.013	0.025
Water/binder	0.56	0.56	0.55	0.50
Flow spread(mm)	-	710	700	680
t_{500} (sec)	-	2.42	2.65	2.35
t_{200} (sec)	-	0.45	0.51	0.36
t_{400} (sec)	-	0.95	1.04	0.80
Level-off (sec)	-	8.36	9.26	6.80
Compressive strength (MPa)	**40**	**35**	**45**	**60**

In the slump cone test, the time for the SCC mix to spread to a diameter of 500 mm after the cone filled with the mix has been suddenly lifted (t500) was recorded, as well as the diameter of the spread when the flow stopped (BS 12350-8, 2010). The resistance to segregation was checked visually. Figures 3.1 , 3.2 and 3.3 show the horizontal spread of SCC Mix 1, Mix 2 and Mix 3, respectively. All mixes so proportioned fall into the viscosity class 2 (VS2) with t500 ≥ 2 sec which indicates a moderate viscosity of SCC mixes (BS EN 206-9, 2010).

Figure 3.2: Horizontal spread of SCC Mix 1

Figure 3.3: Horizontal spread of SCC Mix 2

Figure 3.4: Horizontal spread of SCC Mix 3

3.3.1.4 Passing ability test

All the above developed mixes (Mix 1, Mix 2, Mix 3, Mix 4, Mix 5 and Mix 6) that satisfied the flow-ability criterion and showed no signs of segregation, were subjected to the passing ability test using the J-ring and L-box to ensure that they were able to pass through the narrow gaps that exist between reinforcing bars in a real reinforced concrete structural element.

For this purpose, a 300 mm diameter J-ring apparatus with 16 steel rods (each of diameter 16 mm) was used, as recommended by The European Federation of National Trade Associations (EFNRC, 2005). Details of this test were fully described in Chapter 2.

Mixes that pass the flow-ability test may not necessarily meet the passing ability criterion, especially when large aggregates and fibres are present in the SCC mix. Figure 4.10 shows fibres and large aggregates are nested around the steel rods in an earlier trial version of Mix 6 that had met the flow-ability criterion. In such instances, the paste content had to be increased. The final results of SCHSFRC (Mix 6 shown in Table 3.2) indicated that Mix 6 meets the flow-ability, passing ability and shows no signs of segregation (BS EN 12350-12, 2010). This mix reached the target 28-day compressive strength of 100 MPa.

Figure 3.7: Flow and passing ability of SCC Mix 2 (left) and Mix 3 (right)

Figure 3.8: Flow and passing ability of SCC Mix 4

Figure 3.9: Flow and passing ability of Mix 5 (left) and Mix 6 (right)

Figure 3.10: Fibres and large aggregates are nested around the steel rods in an earlier trial version of Mix 6 that had met the flow-ability criterion

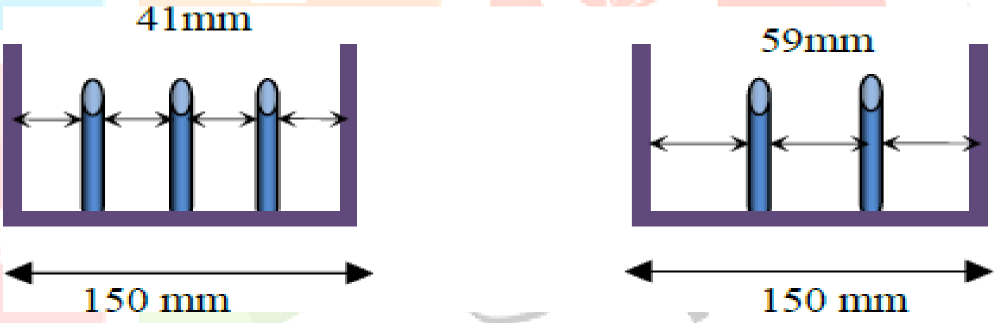
All the SCC mixes in Tables 4.1 and 4.2 met the passing ability criterion based on (BS EN 12350-12, 2010), EFNRC (EFNRC, 2005) and PCI (PCI, 2003) recommendations (Figures 3.7-3.9).

It should be mentioned that slump cone and J-ring tests can be performed by using an upright or inverted cone. We have used both orientations and observed that in the inverted orientation the flow time t500 is slightly increased when large coarse aggregates are present. There was no discernible difference when such aggregates were absent, as in the mix of self-compacting ultra-high performance concrete which will be described later in this Chapter (Section 3.3.2).

4.3.1.5 L-box test

In order to test the ability of a SCC mix to fill the formwork containing reinforcement under its own weight, the L-box apparatus with adjustable steel rods (each of diameter 12mm) was used (BS EN 12350-10, 2010; EFNRC, 2005; PCI, 2003). The vertical leg of the L-box is filled with the SCC mix. At the bottom of this leg is a gate with two or three rods in front of it. When the gate is lifted, the mix flows into the horizontal part of the L-box through the gaps between the rods. The times for the mix to reach 200 mm (t200) and 400 mm (t400) from the vertical leg are recorded, as well as the time it takes the mix to level off in the horizontal leg of the L-box. Again, it is required that no large aggregate particles or fibres be blocked by the rods.

The clearance between the bars when using 2 bars and 3 bars is 59∓1mm and 41∓1mm, respectively as illustrated in Figure 3.11.



At least 14 litres (BS EN 12350-10, 2010) of concrete were prepared in a pan mixer and measurements were recorded.

Figure 3.12: Flow and passing ability of SCC Mix 1 (left) and Mix 2 (right)

Three steel rods were used for SCC mixes (Mix 1, Mix 2, Mix 3) and SCHSC mixes (Mix 4, Mix 5), while for the SCHSFRC mix with 30 mm steel fibres (Mix 6) only 2 rods were used based on the recommendation of (Tviksta, 2000) as wider gaps can be used when fibres are introduced to the mix which should be 1 -3 times the maximum length of fibres used. All designated mixes that had passed the J-ring test also passed the L-box test without any alteration. The passing ability of the SCC mixes is evident from Figures 3.12 to 3.14. The compressive strength of those mixes was measured in the hardened state at 28 days age. The results are reported in Table 3.1 and Table 3.2.

Figure 3.13: Flow and passing ability of SCC Mix 3 (left) and Mix 4 (right)

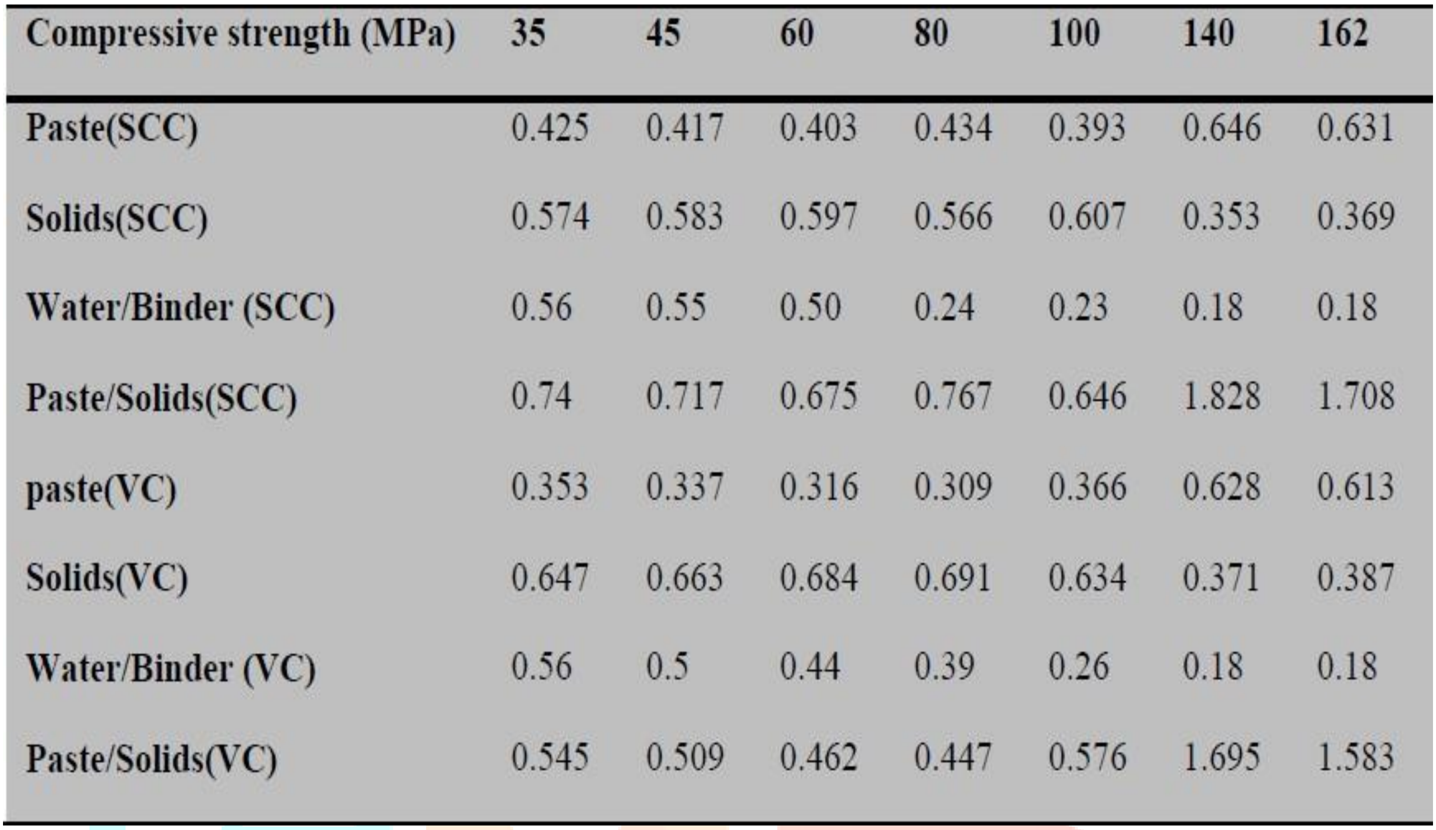
Figure 3.14: Flow and passing ability of SCC Mix 5 (left) and Mix 6 (right)

Constituents	CARDIFRC Mix I	Mix 7	Mix 8
Cement (kg)	855	543.5	543.5
Micro-silica (kg)	214	214	214
Ground granulated blast furnace slag (GGBS) (kg)	-	311.5	311.5
Limestone	-	-	-
Coarse aggregates (kg) (crushed limestone) <10mm	-	-	-
Sand< 2mm	-	-	-
Quartz Sand (kg)			
9-300 µm	470	470	470
250-600 µm	470	470	470
Water (kg)	188	188	188
Fibres 6mm (diameter 0.16 mm) (kg)	390		
Fibres 13mm (diameter 0.16 mm)(kg)	78		
Fibres (30mm long with crimped ends)(kg)		-	195
Super-plasticiser/water	0.15	0.28	0.28
Water/binder	0.18	0.18	0.18
Flow spread(mm)		910	850
t_{500} (sec)		3	3
t_{200} (sec)		0.3	1.9
t_{400} (sec)		0.75	5.6
Level-off (sec)		0.95	54
Compressive strength (MPa)	**200**	**140**	**160**

Table 3.3. Original CARDIFRC Mix I. Mix 7 and Mix 8 are mix proportions of SCUHPC and SCUHPFRC mixes, respectively meeting the flow-ability, passing ability and resistance to segregation criteria.

The composition of this mix with SP/water ratio of 0.28, designated Mix 7 is given in Table 4.3. The horizontal spread in the cone test is shown in Figure 3.15 (left) reaching a spread of 900 mm, with the spread t500 timed at 3 sec. 2.5% by volume of steel fibres were added to this mix. The fibres were evenly distributed in the mixer, as described above, and the resulting SCUHPFRC, designated Mix 8 in Table 3.3 and shown in Figure 3.15 (right), was found to satisfy the flow-ability, passing ability and resistance to segregation criteria , albeit with a reduced final flow spread (850 mm). Visual inspection showed that the fibres were evenly distributed throughout the slump spread.

Table 3.4. Comparison of paste to solids ratio by volume between SCC and VC mixes of equal compressive strength (Deeb and Karihaloo, 2013)



Compressive strength (MPa)	35	45	60	80	100	140	162
Paste(SCC)	0.425	0.417	0.403	0.434	0.393	0.646	0.631
Solids(SCC)	0.574	0.583	0.597	0.566	0.607	0.353	0.369
Water/Binder (SCC)	0.56	0.55	0.50	0.24	0.23	0.18	0.18
Paste/Solids(SCC)	0.74	0.717	0.675	0.767	0.646	1.828	1.708
paste(VC)	0.353	0.337	0.316	0.309	0.366	0.628	0.613
Solids(VC)	0.647	0.663	0.684	0.691	0.634	0.371	0.387
Water/Binder (VC)	0.56	0.5	0.44	0.39	0.26	0.18	0.18
Paste/Solids(VC)	0.545	0.509	0.462	0.447	0.576	1.695	1.583

Table 3.4 shows that, for the same compressive strength and almost the same water to binder ratio, the paste to solids ratio in a SCC mix is much higher than in the counterpart vibrated concrete. However, the difference reduces as the strength of the mix increases.

Chapter 4

Conclusions and Recommendations for Future Research

4.1 Conclusions

From the research work embodied in Chapters 4 to 7, the following major conclusions can be drawn:

- The development of self-compacting concrete mixes is a complex process requiring the resolution of conflicting demands of flow-ability and non-segregation which can be achieved by increasing the paste content and decreasing the large aggregate volume. Self-compacting normal, high-strength and ultra-high-performance concrete mixes without fibres may be designed to satisfy only the flow-ability and cohesiveness (i.e. resistance to segregation) criteria using the slump cone flow test. The resistance to segregation was checked visually only.
- Adding long steel fibres with crimped ends to the self-compacting concrete mix can improve the ductility, toughness, flexural and shear strengths of cement-based materials by

bridging the micro- and macro-cracks and preventing their coalescence. However, the addition of fibres compromises the ability of the mix to flow smoothly through gaps in the reinforcement and to cause segregation of the fibres. Therefore, in the mixes with fibres, it is additionally necessary to check that the mixes meet the passing ability criterion using the J-ring and L-box tests. Our investigations show that although the mixes with fibres meet the flow-ability criterion and are resistant to segregation, as judged by the slump flow test, they may not meet the passing ability criterion. These mixes need to be more flow-able than required by the slump flow test, in order to satisfy the passing ability test .

- The measurement of the plastic viscosity of heterogeneous SCC, especially those containing long fibres using the rheometers often gives inaccurate results with a large scatter. The viscosity of SCC mixes with and without fibres produced in Chapter 4 can be accurately estimated using a micromechanical procedure based on the measured viscosity of the cement paste alone, and the mix proportions. The 30 mm long, 0.55 mm diameter steel fibres with crimped ends significantly increase the viscosity of SCC mixes with fibres .
- The plastic viscosity of SCC mixes with and without fibres so developed is accurately estimated using a micromechanical procedure based on the measured viscosity of the cement paste and the mix proportions.

- A corrected incompressible mesh-less Lagrangian SPH method was implemented to simulate the flow of the non-Newtonian self-compacting concrete with and without fibres whose behaviour is described by a Bingham-type model. This SPH approach offers considerable potential as a numerical method for modelling problems involving large deformations. The simulations of the SCC mixes developed in Chapter 4 emphasised the distribution of large aggregate particles of different sizes throughout the flow in the 3D configuration. On the other hand, the simulation of high strength SCC mixes (compressive strengths in the range 100-160 MPa) which contain between 0.5 and 2.5% by volume steel fibres focused on the distribution of fibres and their orientations during the flow in 3D configuration. The capabilities of this methodology were validated by comparing the simulation results with the slump flow and L-box tests carried out in the laboratory. The numerical results were in excellent agreement with test results and confirmed that the SPH methodology is capable of predicting accurately the SCC flow with and without fibres
- The orientation and the distribution of the steel fibres have been monitored throughout the flow and the change in orientation has been described by the Johnson SB distribution function. It is shown that the fibres tend to align themselves with the principal direction of flow but remain mostly randomly distributed perpendicular to this direction. The reorientation of the fibres during the flow has been used to estimate the fibre orientation factor (FOF) in a cross section perpendicular to the principal direction of flow.
- Several powder-type SCC mixes with different plastic viscosity with and without steel fibre

were proportioned using the SPH simulations as a mix design tool. This method is based on an extensive investigation of the flow characteristics of such mixes using computational simulations, thus avoiding time-consuming laboratory tests .

4.2 Recommendations for future research

- In L-box laboratory test, there was an inevitable delay in manually lifting the gate to release the mix thus increasing the measured times. The delay is the more, the larger the
- content of coarse aggregate and/or fibres in the mix. This problem needs to be solved by providing an alternative method for opening the gate in a single lift.
- only the simulation of flow in confined spaces (L-box) was implemented in 3D configuration. For a full understanding of the passing ability of SCC with or without fibres in unconfined spaces, a 3D simulation of SCC mixes in J-ring test is needed.

- The passing ability of SCC mixes was tested using J-ring and L-box tests. In this thesis,
- The lengthy computational time can be significantly reduced either by using high specification serial computers or by using high performance parallel computers. Since the particle methods such as SPH method are eminently suited for parallelisation, larger 3D configurations can be simulated within a reasonable computational time by the developed algorithms after appropriately parallelising them.

- The maximum size of the coarse aggregate in all the SCC mixes reported was 10 mm. The procedure described for proportioning the SCC mixes can of course be also applied if larger size coarse aggregate (say, 20 mm) is used, especially in mixes with compressive strength up to 60 MPa. It is however necessary to maintain the paste to solids ratio given in Table 4.4. For 35% fly ash replacement, the fresh properties observed were good as compare to 15% and 25% fly ash replacement.

- Decreasing the amount of FA results in a systematic reduction in workability of SCC.
- An increase of about 41.63% of compressive strength at 7 days and 25.55% at 28 days was observed with the decrease of fly ash content from 35% FA to 15% FA.
- An increase of about 28.09% of split tensile strength at 7 days and 26.15% at 28 days was observed with the decrease of fly ash content from 35% FA to 15% FA. Hence if we decrease the FA replacement we can have a concrete with much more compressive and tensile strength.
- Increasing the amount of FA results in a systematic reduction in strength of SCC.
- From economy point of view it has been observed that the cost of M50 SCC is considerably more than conventional M50 by 15.40%.
- But the increase of cost by 15.40% can be compensated on site by curtailing the use of mechanical vibrators, compactors and manpower to operate them.
- However, the cost can also be compensated by avoiding external plastering after removal of formwork as the surface obtained with SCC is quite smoother and doesn’t require any external plastering.
- The speed of construction is also witnessed to be increased with the use of SCC.
- From the research it is concluded that the replacement of FA with cement by 25%. gives the optimum results of workability and strength along with achieving economy.

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