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Fresh and Mechanical Properties of Self-Consolidating Concrete Incorporating Silica Fume and Metakaolin

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FRESH AND MECHANICAL PROPERTIES OF SELF-CONSOLIDATING CONCRETE INCORPORATING SILICA FUME AND METAKAOLIN

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ABSTRACT

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Self-consolidating concrete (SCC) has been gaining greater interest over the past decades with its excellent offerings of efficiency, beauty, and savings. Due to its high flow ability, resistance to bleeding, and non-segregating properties, SCC holds tremendous potential for use in the construction industry. SCC requires no vibration and can fill capacities, including the ones with even the most congested reinforcements. Since SCC can be obtained by incorporating supplementary cementing materials (SCMs) such as silica fume and metakaolin. It is crucial to develop and test different SCC mixtures with different volumes of SCMs to evaluate fresh and mechanical properties. Although silica fume is used in the production of SCC, the use of metakaoline in SCC is new. In this project, eleven SCC mixtures having different volumes of silica fume and metakaolin are developed. In addition, the influence of the above mentioned pozzolans (silica fume and metakaolin) on the fresh and mechanical properties are analyzed. Recommendations on fresh and mechanical properties of silica fume and metakaoline based SCC mixtures are also provided.

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Dedications

To my wife

And

My family

And

To those who support me towards success

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1. INTRODUCTION

1.1 Self-consolidating Concrete

Self-consolidating concrete (SCC) is an innovative concrete that does not require vibration for placing and compaction. SCC is able to flow under its own weight, completely filling formwork and achieving full compaction, even in the presence of congested reinforcement. SCC was developed in Japan in the late 1980s to be mainly used for highly congested steel bar reinforced concrete structures in high activity seismic regions [Ozawa et al. 1989]. The hardened concrete is dense, homogeneous and has the same engineering properties and durability as traditional vibrated concrete.

Self-consolidating concrete has a rapid rate of concrete placement, with faster construction times and ease of flow around congested reinforcement. The fluidity and segregation resistance of SCC ensures a high level of homogeneity, minimal concrete voids and uniform concrete strength, providing the potential for a superior level of finish and durability to the structure. SCC is often produced with low water-cement ratio providing the potential for high early strength, earlier de-molding and faster use of elements and structures.

The elimination of vibrating equipment improves the environment on and near construction and precast sites where concrete is being placed, reducing the exposure of workers to noise and vibration.

The improved construction practice and performance, combined with the health and safety benefits, make SCC a very attractive solution for both precast concrete and civil engineering construction [EFCA, 2005].

The use of SCC is becoming increasingly popular in the United States and Canada. Several departments of transportation are currently accepting SCC mix design in some of their projects [www.trb.org/AM/IP/practical_papers.asp?e=68]. However, because SCC is a relatively new material, its mechanical properties and durability are not fully understood. The main objective of this project is to develop, evaluate and compare the fresh and mechanical properties of new types of SCC mixtures incorporating supplementary cementing materials (SCMs).

1.2 Supplementary Cementing Materials

There is no doubt that concrete is the most extensively used construction material in the world. It is the most consumed substance with an estimated six billion tones production every year [Minerals Commodity Summary-2007]. This is largely due to the abundance of raw material for cement manufacture, low relative cost and the versatility and adaptability of concrete in forming various structural shapes. However, environmental concerns both in terms of damage caused by the extraction of raw material and CO_2 emission during cement manufacture have brought about pressures to reduce cement consumption by the use of supplementary cementing materials. These material may be naturally occurring, industrial wastes or by products or those that require relatively less energy to manufacture. Other concerns that have contributed to these pressures are related to the increase in the number of incidents where concrete structures have experience serious deterioration.

In addressing these concerns and other environmental problems relating to the disposal of waste industrial by-products and also because of economic advantages, mixture of Portland cement (PC) and pozzolans are now commonly used in concrete production.

Originally the term pozzolana was associated with naturally formed volcanic ashes and calcined earths, which react with lime at ambient temperatures in the presence of water. In recent times the term has been extended to cover all siliceous/ aluminous materials which, in finely divided form and in the presence of water, will react chemically with calcium hydroxide (CH) to form compounds that possesses cementitious properties [Bezerra et al. 2006]. This generalized definition covers waste products such as fly ash (FA), rice husk ash, silica fume (SF) and calcined clay in the form of metakaolin (MK). The utilization of supplementary cementing materials or pozzolans results in added technical advantages manifested in reductions in temperature rise and improvements in durability and strength enhancement.

1.3 Objectives

As the infrastructures becomes old the cost of their maintenance and repairs increases. Conventional concrete structures significantly deteriorate with time requiring regular and often costly maintenance. The use of SCC with good mechanical and durability properties can minimize deterioration of structures and hence minimize the maintenance cost. Improved understanding of the characteristics of SCC will increase its use in construction industry.

This project is intended to develop SCC mixtures incorporating pozzolanic materials as replacement of cement. The objectives of this project include:

- The review of previous research studies conducted on self-consolidating concrete covering fresh and mechanical properties.
- Development of self-consolidating concrete mixes with two natural pozzolans such as silica fume and metakaoline as replacement of cement.
- Investigation on the performance of developed SF and MK based SCC mixtures based on the test results of fresh and mechanical properties.
- Making recommendations for suitable SF and MK based SCC mixtures for construction applications.

1.4 Scope

The scope of this project includes literature review and an experimental investigation covering mix design, fresh and mechanical properties tests in order to develop SCC mixes using different combinations of silica fume and metakaolin as replacement of cement. Although metakaoline has been used in the development of concrete mixtures in past research studies [Wild et al. 2001; Tafraoui et al. 2008; Rafat and Klaus, 2009; Lagier et al. 2007; Poon et al. 2003; Khatib and Hibbert, 2005] its use in SCC is new. Fresh property tests include slump flow with J-ring, V-funnel flow time, L-box, U-box and settlement. Mechanical properties tests include compressive and tensile strengths at different ages.

Analysis of test results and recommendations on SCC mix design are also included in the scope of this project. Various aspects of the research conducted on SCC will be described in various chapters of this project.

Chapter 2 provides a literature review of previous research studies and information relevant to SCC including materials, design concepts, properties and applications.

Chapter 3 presents the experimental program highlighting material used and their properties/specifications. It also describes the methodology that applied on mix proportion of SCC as well as testing fresh and mechanical properties. The mixing, casting and curing methods are also described.

Chapter 4 describes the results and discussions on fresh and mechanical properties of developed SCC mixtures.

Chapter 5 represents the conclusion of this project with future research recommendations.

2. LITERATURE REVIEW

Concrete is a construction material composed of cement (commonly Portland cement) as well as other supplementary cementitious materials (SCMs) such as fly ash, silica fume and slag cement, aggregate (generally a coarse aggregate such as gravel, limestone, or granite, plus a fine aggregate such as sand), water, and chemical admixtures [http://en.wikipedia.org/wiki/Concrete]. The word concrete comes from the Latin word "concretus", which means "hardened" or "hard".

Concrete solidifies and hardens after mixing with water and placement due to a chemical process known as hydration. The water reacts with the cement, which bonds the other components together, eventually creating a stone-like material. Concrete is used to make pavements, architectural structures, foundations, motorways/roads, bridges/overpasses.

Concrete is used more than any other man-made material in the world. As of 2006, about 7 cubic kilometers of concrete are made each year—more than one cubic meter for every person on Earth. Concrete powers a US $35-billion industry which employs more than two million workers in the United States alone. More than 55,000 miles (89,000 km) of highways in America are paved with this material. The People's Republic of China currently consumes 40% of the world's cement/concrete production [http://wapedia.mobi/en/Concrete].

Concrete is a material that literally forms the basis of our society. Actually concrete is brittle under tensile loading and its mechanical properties could be improved by adding fibers which prevent or control propagation of cracks. The incorporation of fibers enhances the structural performance of concrete, including the reduction of spelling of the cover over reinforcement in column elements, the increase in shear strength of beams, as well as the enhancement of ductility of beam-column connections [Khayat and Roussel, 2000].

This chapter provides a literature review on the current state of the art technology of self-consolidating concrete by summarizing design methodology and fresh /mechanical properties as well as structural performance.

2.1 Self -Consolidating Concrete

Self-consolidating concrete (SCC) also known as self compacting concrete, is a highly flow able, non segregating concrete that can spread into place, fill the formwork and encapsulate the reinforcement without any mechanical consolidation.

Self-consolidating concrete initially was developed in Japan in late 1980s to be mainly used for highly congested steel bar reinforcement structures in high activity seismic regions [Ozawa et al. 1989]. SCC generated great interest worldwide due to certain cost effective advantages over normal concrete. However, gaining acceptance of SCC in the cast-in-place market is a matter of education than promotions and the benefits of SCC do not always come easily or immediately. Like with all new products, there is a learning curve for using SCC [Joe 2003].

SCC isn't a new idea, although the SCC technology is different from what it was in the past. Marketing of "flowing concrete" started in the early 1980's in the United States after the introduction of super plasticizers. In 1989, Master Builders Cleveland, developed and marketed a high strength concrete with a slump flow of 580 mm to 660 mm in a high rise application. This concrete, however, still required some minimal vibration for consolidation [Joe 2003].

Some of the advantages of using SCC are:

- Can be placed at a faster rate with no mechanical vibration resulting in savings in placement costs.
- Improved and more uniform architectural surface finish with little to no remedial surface work.
- Ease of filling restricted sections and hard to reach areas. Opportunities to create structural and architectural shapes and surface finishes not achievable with conventional concrete.
- Improved consolidation around reinforcement and bond with reinforcement.
- Improved pump ability.

- Improved uniformity of in-place concrete by eliminating variable operator-related effort of consolidation.
- Labor savings and
- Shorter construction periods and resulting cost savings.
- Quicker concrete truck turnaround times enabling the producer to service the project more efficiently.
- Reduction or elimination of vibrator noise potentially increasing construction hours in urban areas.
- Minimizes movement of ready mix trucks and pumps during placement.
- Increased job site safety by eliminating the need for consolidation [www.nrmca.org/aboutconcrete/cips/37p].

Although SCC is not expected to ever completely replace conventionally vibrated concrete, the use of the material in both the precast and ready mix markets in the UK, Europe and the rest of the world is expected to continue to increase as the experience and technology improve, the clients demand a higher quality finished product while the availability of skilled labor continues to decrease [Goodier 2003].

2.2 Methodology of SCC

Several different approaches have been used to develop SCC. One method to achieve self consolidating property is to increase significantly the amount of fine materials or mineral admixtures, for example fly ash (FA), ground granulated blast furnace slag (GGBFS), silica fume, limestone (LS) filler, volcanic ash (VA) or cement kiln dust (CKD) without changing the water content compared to common concrete [Khayat et al. 1997; Bui et al. 2002; Lachemi et al. 2003; Patel et al. 2004; Hossain and Lachemi 2004; European SCC Guidelines, 2005]. The use of such mineral admixtures can improve the slump flow and cohesiveness, reduce the segregation, lower the cost by replacing relatively costlier cement, lower the heat of hydration, lower the permeability and lower the shrinkage and creep of SCC. Mineral admixtures can also exert beneficial effect on concrete for the improvement of interfacial transition zone [Gue et al. 2007]. GGBFS provides reactive fines with a low heat of hydration. A high proportion (more than 30 % of binder) of GGBFS may affect stability of SCC while slower setting can also increase the risk of segregation [European SCC Guidelines, 2005]. The high level of fineness and spherical shape of silica fume results in good cohesion and improved resistance to segregation when used in SCC. However, silica fume is also very effective in reducing or eliminating bleed and this can give rise to problems of rapid surface crusting. This could result in cold joints or surface defects if there are any breaks in concrete delivery and also the difficulty in finishing the top surface [European SCC Guidelines 2005].

One alternative approach to produce SCC consists of incorporating a viscosity modifying admixture (VMA) to enhance stability [Rols et al. 1999; Lachemi et al. 2004]. The use of VMA along with adequate concentration of super plasticizer (SP) can ensure high deformability and adequate workability leading to a good resistance to segregation.

To avoid segregation, SCC utilizes a limited aggregate content and super plasticizer as well as low water-to–powder ratio [Okamura and Ouchi 2003]. SCC performance is highly affected by the characteristics of the ingredient materials such as size, shape, surface area and grain size distribution of aggregates [Saak et al. 2002]. SCC may be classified into three types: the powder type, viscosity agent type and the combination type [EFNARC 2006]

- In the powder type, SCC is characterized by the large amount of powder (all material < 0.15 mm), usually in the range of 550 to 650 kg/m^3. The powder provides the plastic viscosity and hence, the segregation resistance of the mix.
- In the viscosity type SCC, the powder content is lower (350 to 450 kg/m^3). The segregation resistance is mainly controlled by a VMA and the yield stress by the addition of SP.
- In the combination type SCC, the powder content varies from 450 to 550 kg/m^3 but in addition the rheology is also controlled by a VMA as well as an appropriate dosage of SP. The purpose of the addition of a VMA is to replace or limit the addition of fines, thus making a fresh concrete more cohesive [EFNARC 2006].

All types of cements can be used in the SCC production, but should develop a satisfactory interaction and compatibility with chemical additives, viscosity modifying admixtures and super plasticizers.

Super plasticizers improve workability and strength of concrete with reduced water-to- cement ratio (w/c). SPs are also often used when pozzolanic materials are added to concrete to improve strength. SPs have been manufactured from sulfonated naphthalene formaldehyde or sulfonated melamine formaldehyde. New products based on polycarboxylic ethers (PCE) are also developed. PCEs are not only chemically different from the older sulphonated melamine and naphthalene based products, but their action mechanism is also different, giving cement dispersion by steric stabilization, instead of electrostatic repulsion. This form of dispersion is more powerful in its effect and gives improved workability retention to the cementitious mix. Furthermore, the chemical structure of PCE allows for a greater degree of chemical modification than the older products, offering a range of performance that can be tailored to meet specific needs [Zhong et al. 2006]. Nephthalene and melamine super plasticizers are organic polymer. The long molecules wrap themselves around the cement particles, giving them a highly negative charge so that they repel each other [Khayat 1998]. The workability of SCC and performance of hardened concrete depend on the type of SP [Khayat and Hwang 2006].

There is no standard method for SCC mix design and many academic institutions and contracting companies have developed their own mix proportioning methods. Mix design often use volume as a key parameter because of the importance of the need to over fill the voids between the aggregate particles. Some methods try to fit available constituents to an optimized grading envelope. Another method is to evaluate and optimize the flow and stability of the paste and then the mortar fractions before the coarse aggregate is added and the whole SCC mix tested.

Sixty eight case studies on application of SCC (from 1993 to 2003 in different countries) have been analyzed with details [Domone 2006]. A clear majority (70 %) of cases used aggregate with a maximum size between 16 and 20 mm. The use of crushed rock or gravel aggregate seemed to depend on local availability. Approximately half the cases used a VMA in addition to super plasticizer and could therefore be considered as a combined type of SCC. Limestone was the most common addition (41 % of the cases). Median value of the key mix proportions were coarse aggregate content of 31.2 % by volume, paste content of 34.8% by volume, powder content of 500 kg/m^3, water powder ratio of 0.34 weight and fine aggregate/ mortar of 47.5 % by volume. In ninety percent of the cases, SCC with slump flow in the range of 600-750 mm was used while 80% had compressive strengths in excess of 40 MPa [Domone 2006].

2.3 Supplementary Cementing Materials

Pozzolans, such as fly ash or dust powder, could be used as an alternative. These can be used to replace the cement content in the SCC. Some advantages include that they do not only reduce the required cement but also fill the capillary pores. This translates into a denser and durable mix. The solution to the lowered flow ability, can be solved by using some pozzolans, including fly ash and slag. Increase flow ability then directly influences the amount of super plasticizers being used, therefore reducing production costs. There are significant changes to the SCC's mechanical properties, however, if any change to volume of coarse aggregate, and any increases in the volume of cement paste are made.

The cementing materials normally used in North America include the ordinary Portland cement, silica fume, fly ash, and slag. Aggregates used include river sand and crushed aggregates. It is important to note that the size and type of such aggregates influence the mix's consolidation and distribution. In addition to those, many admixtures (such as water-reducing agents) are used in the designs of the SCC mixes. All in all, these supplementary cementing materials are often added to enhance the SCC's feasibility in terms of its costs, permeability, strength, or to simply influence or improve upon the SCC's other properties.

Some of the common supplementary cementing materials are discussed in the following sections.

2.3.1 Metakaolin as Supplementary Cementing Material

There are compelling reasons, in the long term, to extend the practice of partially replacing cement in concrete and mortar with waste and other less energy intensive process material, which have pozzolanic properties. One possible source for a pozzolan is calcined clay.

Natural pozzalans in the form of calcined earth blended with lime have been used to produce cementitious materials for thousands of years. Structures such as water tanks, aqua ducts, walls and bridges 4000 years old have been constructed from thermally activated clay and lime mortars [Sabir et al. 2001].

The utilization of calcined clay in the form of metakaolin (MK) as a pozzalonic addition for mortar and concrete has received considerable interest in recent years. Much of this interest has focused on removal of the calcium hydroxide (CH), which is produced by the hydration of cement and which is associated with poor durability [Sabir et al. 2001]. CH removal has a major influence on resistance of sulfate attack and alkali silica reaction (ASR), and also provides enhanced strength, which is derived from the additional cementitious phases generated by reaction of CH with MK [Sidiqqui and Klaus 2008]. MK is produced from high purity Kaolin clay by calcinations at moderate temperature (650-800°C). It contains silica and aluminia in an active form which will react with the CH. The principal reason for the use of clay based pozzolans in mortar and concrete have been materials availability and durability enhancement. In addition, depending on the calcining temperature and clay type, it is also possible to obtain enhancement in strength, particularly during the early stages of curing. The very early strength enhancement is due to a combination of the filler effect and accelerated cement hydration. Subsequently, these effects are enhanced by the pozzolanic reaction between MK and CH produced by the hydration of the cement.

2.3.2 Pozzolanic Reaction of Metakaolin

It is known that thermal activation in air (at 600-900°C) of many clay mineral leads, dehydroxylation, to break down or partial break down of the crystal lattice structure forming a transition phase with high reactivity. A typical example is the production of Metakolinite ($Al_2O_3.2SiO_2$) or AS_2 by calcining clay or lateritic soil rich in kaolinite. The chemical reactions involved when calcined clays are used as pozzolanas for concrete have been discussed by Malquori and Turrizani, 2001 and more recently by DeSilva et al. 2004 and Dunster et al. 2004. The principal reaction is that between the AS_2 and the CH derived from cement hydration, in the presence of water. This reaction forms additional, cementitious aluminum containing CSH gel, together with crystalline products, which include calcium, aluminate hydrate and aluminio-silicate hydrates (i.e. C_2ASH_8, C_4AH_{13} and C_3AH_6). The crystalline products form, depend principally on the AS_2/CH ratio and the reaction temperature. In addition if carbonate is freely available carbo-aluminates may also be produced. The optimum replacement levels of PC by MK are associated with changes in the nature and proportion of the different reaction products (depending on composition) temperature reaction time, which are formed in the PC-MK system.

2.3.3 Effects of Metakaolin on Durability and Compressive Strength

There have been several studies on the strength development of concrete containing MK. These studies have demonstrated clearly that with intelligent use considerable enhancement in strength, particularly at the early stages of curing, can be produced. Caldarone et al.-1994 produced concretes, with 5% and 10% MK, which showed enhanced strengths at ages up to 365 days. They reported that their MK-PC concretes exhibited strengths, which were slightly greater than SF-PC mixtures at the same levels of cement replacement by the pozzolans. Similar influences of MK on the strength of concrete have been reported by Wild et al. 2001. They identify three elementary factors, which influence the contribution that MK makes to concrete strength. These are the filler effect, the acceleration of PC hydration- which occurs within the first 24 hours, and the pozzolanic reaction which has its maximum effect within the first 7-14 days for all MK levels between 5 % and 30 %. The degree to which strength is enhanced declines beyond 14 days, although strength gain relative to the control concrete are still present after 90 days. Also little strength advantage is gained for MK level excess of 15 %. Similar findings were observed in where strength gain in mortars containing 15% MK continued after 180 days.

There is strong evidence that MK greatly influences the pore structure in pastes and mortars and produces substantial pore refinement. This leads to significant modification to the water transport properties and diffusion rates of harmful ions. It has been reported that MK reduces the volume of capillary pores of sizes (0.05-10) normally associated with increased permeability. The rate of water absorptions of mortar is halved by replacing 20% of the cement by MK [Bai et al. 2001]. The refinement of the pore structure affected by the MK was also found to reduce the rate of ingress of chloride ions onto the concrete. Significant reduction in the values of the diffusion coefficient was obtained when 15% of the cement was replaced by MK. In addition, Coleman and Page (1997) have shown that cement pastes blended with 10% or 20% MK exhibited higher capacities than plain PC pastes, to bind chloride ions introduced by contamination of the mix water, thus reducing the Cl^- concentration in the pore solution. The MK also produces a long-term reduction in pore solution hydroxide ion concentration. However, although there is a reduction in pore solution pH, the $[Cl^-]/[OH^-]$ ratios are similar to those in equivalent plain PC pastes, from which it is concluded that inclusion of up to 20% MK will have little effect on the risks of chloride induced corrosion of embedded steel.

2.3.4 Silica fume as Supplementary Cementing Material

Silica fume also called condensed silica fume or micro silica is a fine, dark grey or black residue often used in the creation of high-strength concrete. It is resulted from the production of silicon or ferro-silicon alloys (as well as a byproduct in the reduction of high-purity), which are carried, through the exhaust gases, from the place of production (normally a furnace) [Luther 1990]. Silica fume has a low density and a high surface area. Silica fume consists of very fine vitreous particles with a surface area on the order of 215,280 ft^2/lb (20,000 m^2/kg) when measured by nitrogen adsorption techniques, with particles approximately 100 times smaller than the average cement particle [US Department of Transportation 1998].

Due to its high fineness and silica content, it is very effective and offers reactive pozzolanic activity. Silica fume is often added to Portland cement concrete to enhance its properties in particular, its compressive strength, bond strength, and abrasion resistance. The reason behind this is because of the addition of such a fine powder, as well as the pozzolanic reactions with the calcium hydroxide in the cement paste. The use of silica fume as a SCM also helps the reinforcing steel in the concrete resist corrosion as it reduces the permeability to chlorine ions [William and Kohin 2002]. This is especially useful in regions where the environmental chlorine levels are high, such as the coastal regions and saltwater bridges. Before 1970s, all silica fumes that produced were dumped into the atmosphere. However, that soon changed as health issues were brought to the limelight. This led to the land filling of silica fume in the later years, as well as it opened up opportunities for silica fume to be incorporated into other applications, especially in high-performance concrete. Its uses have branched since then, and it is often viewed as a powerful addition to the concrete to produce very high-strength, low permeability, and chemically resistant concrete. After environmental concerns necessitated the collection and land filling of silica fume, it become economically justified to use silica fume in various applications, in particular high performance concrete [en.wikipedia.org/wiki/Silica fume].

Silica fume is used to produce very durable, high strength concrete with very low permeability and low rebound shotcrete. Silica fume chemically reacts with calcium hydroxide in cement paste acting as a super pozzolan. This reaction yields a calcium silicate hydrate gel enhancing strength and durability by consuming the weak calcium hydroxide crystals. The ultra-fine amorphous silica particles also help fill the voids between cement particles further contributing to the formation of an extremely dense, less permeable concrete. Higher strengths make new structural designs possible by reducing column sizes, production, transportation, and erection costs. The lower chloride permeability makes microsilica concrete produced with silica fume highly suitable for parking structures, bridge decks, marine structures or wherever distress due to corrosion of embedded steel can result.

[www.targetproducts.com/catalog/specsheets/silicafumedensified].

2.3.5 Fly Ash

Fly ash is one of the residues generated in the combustion of coal. Fly ash is generally captured from the chimneys of coal fired power plants and is one of the two types of ash that jointly are known as coal ash: the other bottom ash, is removed from the bottom of coal furnaces. Depending upon the source and makeup of the coal being burned, the components of fly ash vary considerably.

In the past, fly ash was generally released into the atmosphere, but pollution control equipment mandated in recent decades now require that it may be captured prior to release. In the US, fly ash is generally stored at coal power plants or placed in landfills. About 43% is recycled often used to supplement Portland cement in concrete production [National Research Council of the National Academics 2006].

Fly ash material solidifies while suspended in the exhaust gases and is collected electrostatic precipitators. Since the particles solidify while suspended in the exhaust gases, fly ash particles are generally spherical in shape and range in size from 0.5 µm to 100 µm. They consist mostly of silicon di oxide (SiO_2) which is present in two forms: amorphous, which is rounded and smooth, and crystalline, which is sharp, pointed and hazardous; aluminium oxide (Al_2O_3) and iron oxide (Fe_2O_3). Fly ashes are generally highly heterogeneous, consisting a mixture of glassy particles with various identifiable crystalline phases such as quartz, mullite and various iron oxides [Scott et al. 2007]. Fly ash also contains environmental toxins in significant amounts. Toxic constituents include arsenic, beryllium, boron, cadmium, chromium, chromium VI, cobalt, lead, manganese, mercury, molybendum, selenium, strontium, thallium and Vanadium along with dioxins and PAH compound [American Coal Ash Association, www.acaa-usa.org].

Two classes of fly ash are defined by ASTM C618: Class F Fly ash and Class C fly ash. The chief difference between these classes is the amount of calcium, silica, alumina, and iron content in the ash. The chemical properties of the fly ash are largely influenced by the chemical content of the coal burned (i.e anthracite, bituminous and Iignite) [American Coal Ash Association 2009].

Not all fly ashes meet ASTM C618 requirements, although depending on the application, this may not necessary. Fly ash used as a cement replacement must meet strict construction standards, but no standard environmental standards have been established in the United States. 75% of the fly ash must have a fineness of 45μm or less, and have a carbon content measured by the loss on ignition of less than 4%. The particle size distribution of raw fly ash is very often fluctuating constantly, due to changing performance of the cal mills and the boiler performance. This makes it necessary that fly ash used in concrete needs to be processed using separation equipment like mechanical air classifiers.

When Portland cement is mixed with water, most of the cement forms insoluble cementitious compounds, CaOH is formed as part of this reaction. When fly ash is introduced into concrete, it reacts with the CaOH to form additional cementitious compounds. In a properly proportioned mix, fly ash can improve many of the properties of concrete, including improved workability and consolidation, increased flexural and compressive strengths, improved pump ability, and decreased permeability [Duxson et al 2007].

Fly ash provides a significant contribution to sustainable construction. The use of this material in concrete production consumes less energy and offers improved efficiency and building performance.

2.3.6 Ground Granulated Blast Furnace Slag (GGBS or GGBFS)

Ground granulated blast furnace slag (GGBS or GGBFS) is obtained by quenching molten iron slag (a byproduct of iron and steel making) from a blast furnace in water or steam, to produce a glassy, granular product that is then dried and ground into a fine powder. In the production of iron, iron ore, iron scrap, and fluxes (limestone and / or dolomite) are charged into a blast furnace along with coke for fuel. The coke is combusted to produce carbon mono oxide, which reduces the iron ore to a molten iron product. This molten iron product can be cast into iron products, but is most often used as a feedstock for steel production. Blast furnace slag is a nonmetallic co product produced in the process. It consist primarily of silicates, aluminosilicates and calcium-aluminia silicates. The molten slag, which absorbs much of sulfur from the charge, comprises about 20 % by mass of iron production [British Standard Institute 1983].

GGBS is used to make durable concrete structures in combination with ordinary Portland cement and / or other pozzolanic materials. GGBS has widely used in many parts of the world for its superiority in concrete durability, extending the life span of building from fifty years to a hundred years [http://www.heidelbergcement.com/NR/rdonlyres/3074C118-5D39-4E44-91C3-514A20E79CD/0/GGBS_Durability.pdf].

Concrete made with GGBS cement sets more slowly than concrete made with ordinary Portland cement, depending on the amount of GGBS in the cementitious material but also continue to gain strength over a long period in production conditions. This result in lower heat of hydration and lower temperature rises, and makes avoiding cold joints easier, but may also effect construction schedules where quick setting is required [U.S. Federal Highway Administration, 24-01-2007].

Use of GGBS significantly reduces the risk of damages caused by alkali-silica reaction (ASR), provides higher resistance to chloride ingress-reducing the risk of reinforcement corrosion- and provides higher resistance to attacks by sulfate and other chemicals. GGBS cement is added to concrete in the concrete manufacturer's batching plant, along with Portland cement, aggregates and water. The normal ratios of aggregate and water to cementitious material in the mix remain unchanged. GGBS is used as a direct replacement for Portland cement, on a one-to-one basis by weight. Replacement levels for GGBS vary from 30 % to up to 85 %. Typically 40 to 50 % is used in most instances. [http://en.wikipedia.org/wiki/Ground_granulated_blast_furnace_slag].

2.4 Benefits of Supplementary Cementing Materials

The supplementary cementing materials provide the following structural, economic and environmental benefits to concrete:

Structural

- The use of finely-divided particles tends to provide enhanced workability.

- Water requirement is reduced at a given consistency for materials that have low surface area.
- Ultimate strength, impermeability, and durability against chemicals is greatly increased.
- Thermal cracking resistance is improved because of the lower heat of hydration of cements, and increased tensile strain capacity.

Economic

- Portland cement is the most expensive part of the SCC mix, and can easily be replaced by supplementary cementing materials (SCM), which cost a fraction of the Portland cement.

Environmental

- CO_2 emissions are reduced (in comparison to Portland cement whose production releases one ton of emissions for every ton produced.
- Since SCMs (especially fly ash and silica fume) generally require little energy-intensive operations to be used, emissions are reduced as well.

2.5 Fresh Properties of Self-consolidating Concrete

SCC fresh properties are characterized by its deformability and stability as well as its bleeding and segregation resistance. SCC remarks its capacity to flow homogeneously without segregation between ingredients or bleeding. The method for achieving self compact ability 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 and Ouchi 2003]. SCC should have static and dynamic stability without bleeding or surface settlement prior to stiffening [Bui et al. 2002; Khayat et al. 2004]. The lack of static stability can cause surface defects, including the presence of bleed channels. Bleeding and settlement can decline the quality of the interface between aggregate and cement paste with direct bearing on impermeability and hardened mechanical properties [Khayat and Guizani 1997]. SCC fresh properties are described in the following sections.

2.5.1 Deformability

Deformability can be defined as the ability of a SCC to flow in a heavily reinforced section and other restricted areas. Highly flow able SCC should have relatively low yield stress to ensure good deformability. Inter-particle friction between coarse aggregate, sand, and binder increases the internal resistance of flow, limiting the deformability and speed of flow of SCC [Khayat et al. 1999]. Such friction can be high when concrete flows through restricted spacing because of greater chances of collision between various solids. The deformability of SCC can be increased by increasing water to binder ratio (W/B), increasing the dosage of SP, and by incorporating very fine supplementary cementing materials (SCM) [Nanayakkara et al. 1998; Khayat et al. 1999]. Increase in the W/B can secure high deformability but it may affect the mechanical and durability properties of SCC in the long run. Increasing W/B can also reduce cohesiveness and can cause segregation that may leads to blockage during flow. Inter particle friction between binder grains can be reduce by using SP to disperse the cement grain. A high dosage of SP can however lead to segregation and blockage of the SCC flow [Bui et al. 2002; Khayat et al. 1999]. Very fine and glossy textured particle of SCM can reduce the inter-particle friction and lead to higher deformability.

2.5.2 Stability and Segregation

The stability of fresh concrete is characterized by its resistance to segregation, and bleeding and is affected by the mixture proportioning, aggregate shape and gradation, and the placement conditions. When a mixture does not possess an adequate level of stability, the cement paste may not be cohesive enough to retain individual aggregate particles in a homogenous suspension. This causes the concrete constituents to separate, thus resulting in a significant reduction in mechanical properties and durability [Khayat et al. 1999, Bui et al. 2002].

There are two kinds of segregation. The first is the separation of mortar from coarse aggregates and second is bleeding. Bleeding is defined as a phenomenon whose external manifestation is the appearance of water on the top surface after concrete has been placed but before it has set. Bleeding is the form of segregation where solids in suspension tend to move downward under the force of gravity. Bleeding occurs due to the inability of the constituent material to hold all the mixing water in a dispersed state. Some bleeding water reaches to the surface ; large amount of it gets trapped under large pieces of aggregate, and horizontal reinforcing bars, which effect the mechanical performance of concrete such as strength and bond [Bui et al. 2002].

Improper consistency, excessive amount of large particles in coarse aggregate with either too high or too low density, presence of fewer fines (due to low cement and sand contents or the use poorly graded sand) can cause segregation and bleeding in SCC. The concrete without mineral admixtures may suffer segregation and bleeding in concrete. Some of the measures that can be used to enhance the stability of fresh SCC are;

- The reduction in water-to-binder ratio (W/B)
- The increase of cementing material content such as fly ash, GGBFS and other fines
- The incorporation of viscosity modifying admixtures (VMA)

A large decrease in aggregate volume or an increase in water content can reduce the cohesiveness and lead to segregation. A relative high sand-to-total aggregate content of 42-52% is often used to enhance cohesiveness and reduce the risk of segregation and water dilution [Bui et al. 2002].

2.6 Mechanical Properties of Self-consolidating Concrete

The performance of reinforced concrete is significantly influenced by the quality of the concrete. The quality of structural concrete is dependent on the properties of the materials and concrete mix properties. Each constituent within the concrete has an effect on the properties of the structural concrete. Water influences the strength and durability of the concrete. High quantities of Portland cement can increase heat of hydration and cause high rates of drying shrinkage, leading to early cracking in concrete. Aggregate strength and type can have an effect on strength and can contribute to other undesired problems such as alkali aggregate reactions in the concrete. Proportioning structural concrete is dependent on the application and conditions it will subject to. High quality concrete will ensure that the structural performance of the concrete will not be affected by the loss of durability due to deterioration and poor construction practices. Being a fairly new concrete, SCC does have an abundant resources for future research on durability and structural performance. The majority of structural construction with SCC has taken place within the last decade in which all performance related issues are only within a short time frame. The mechanical properties of SCC must be clearly understood in order to determine the design constraints or improvements that can be applied to the design of structural elements with SCC.

2.6.1 Strength and Elastic Modulus of SCC

One of the most important properties of structural concrete is its compressive strength. When designing concrete structures, engineers must specify the compressive strength (f'_c). The compressive strength of normal concrete ranges from 20 to 40 MPa [CPCA 1995]. Usually the compressive strength is determined by testing 150×300 mm cylinders under axial compression at 28 days. The consistency of concrete and its rheological properties are important to produce a concrete without significant variations in strength within a structural element such as column or beam. The VMAs used in SCC are required to retard the effects of super plasticizers (SP) on segregation and bleeding of concrete. The segregation of aggregates can significantly affect the structural performance of the concrete.

Persson (2001) performed a study on the mechanical properties of SCC such as strength, elastic modulus, creep and shrinkage. The data used in the study was taken from experimental studies performed in Japan [Ehara 1998; Klevbo 1999] and Sweden [Byfors and Grauers 1997; Grauers 1998; Dieden 1999; Anderson and Sjokvist 1999]. Various mixes of concrete were designed for their use in beams, piles, slab, T-beams and in tunnel construction. The study included a total of 88 cylinders, half made with normal concrete as reference samples and other half with SCC. The SCC samples used various forms of viscosity fillers such as fly ash, glass fibre, limestone powder, silica fume and quartzite and the water cement ratio ranges from 0.24 to 0.80. One half of the samples tested were sealed airtight with foil to avoid moisture loss and the others were air-cured. Persson (2001) determined that the strength of the concrete tend to be significantly higher with the quartzite filler and low water to cement ratios. He also noted that the comparison between normal concrete and SCC at constant porosity showed small difference in strength. The elastic modulus for both SCC and normal concrete exhibited similar curves regardless of the samples being air cured or sealed.

Researchers from University of Paisley had provided the concrete industry with valuable information for the properties of hardened concrete with several publications and online reports [Sonebi et al. 2000] The studies evaluated the properties of two types of SCC, incorporating limestone powder in the housing concrete (SCCH) and ground granulated blast slag in the civil concrete (SCCC). The reference concrete use Portland cement only. A third type of SCC incorporated steel fibers and limestone powder (FSCC). The W/B was 0.36 for both SCCH and SCCC and 0.68 and 0.43 for the reference concrete (RH and RC), respectively.

The compressive strength of SCC is generally high when incorporating viscosity modifying admixtures (VMA), as compared to normal concrete. This is believed to be attributing to the slight delay of hydration due to addition of VMA. Sonebi et al. (2000) noted that the fine limestone powder develop high early strength due to the accelerated affect on C_3S hydration, where the blast furnace slag delayed hydration in the SCCH to produce lower early strength than the reference concrete. The average 28 days compressive strength of the SCCH and SCCC were 47 and 79.5 MPa, respectively. The reference concrete RH and RC had compressive strength of 37 and 61.5 MPa, respectively. Sonebi et al. (2000) also noted that the difference in air cured 90 days compressive strength was related to the type of filter used in SCC. The limestone powder was less affected by air curing due to accelerated effect on curing and water retentiveness of SCCH. The opposite was found for SCC with blast slag when compared to the reference concrete.

2.7 Research Conducted at Ryerson University

A number of studies on SCC have been conducted at Ryerson University and is still going on. In this section, a brief summary of some of the work already done on SCC at Ryerson University is discussed.

With the incorporation of mineral admixtures (such as fly ash and slag) or viscosity-modifying admixtures, VMAs, SCC can be obtained [Bouzoubaa, N., and Lachemi, M. (2001); Hassan, A.A.A., Hossain, K.M.A., and Lachemi, M. (2008); Patel et al. 2004; Lachemi et al. 2004]. When it comes to stabilizing the rheology of SCC, the use of VMA has proved very effective. A study by Hossain et al. 2004 was conducted to investigate ways to reduce the use of high-range water-reducing admixtures (HRWRA), while at the same time optimizing the utilization of fly ash. They formulated 21 statistically balanced concrete mixtures, and used four independent variables: total binder content (350-450kg/m^3), FA's percentage as cement replacement (30-60% by mass), and HRWRA's percentage (0.1-0.6% by mass), and water-to-binder ratio (0.33-0.45). They concluded that these additions were significant and had a positive influence on the SCC properties. During this study, the Box-Wilson central composite design (CCD) method was used. Fly ash has an excellent ability to reduce the HRWRA demand if a certain slump flow is required. Therefore, both the initial as well as the final setting times are dependent upon the percentages of FA and HRWRA. Higher percentages of these admixtures mean higher setting times. When the binder and HRWRA content were kept constant, the 28-day compressive strength began to decrease as the addition of fly ash increased. The statistical models and response charts that this study generated are essential tools in the mixture design of fly ash. One can use these models to predict the fresh, hardened, and durability properties of SCC mixes, and process the properties of multiple mixtures within a short time frame to conclude the most feasible mix for a certain scenario.

Another study conducted by Hossain et al. 2003 focused on the suitability of four new types of polysaccharide-based VMA for use in SCC mixes. First, to understand the rheological properties, preliminary investigations on mortar with various dosages of VMA was carried out. The study also looked at the influence and feasibility of the new types of VMAs. Soon after, a more comprehensive study was conducted on the SCC mixes to investigate their fresh and hardened properties based on the various tests, with differing dosages of VMAs. The SCC that is currently available on the market is costly simply due to the high price of VMAs and binder volume in the mixture. To overcome this, a cost-effective product is necessary to compete in the construction industry. Within this study SCC mixes that incorporated different types of VMAs were studied. These polysaccharide-based VMAs (suspended in water) were classified as A, B, C, and D. They had a specific gravity of 1.42, while a total solid content of about 81%. It was noted that a satisfactory SCC could be created by using a lesser content of one of these VMAs than the recommended dosage of commercial VMA. This, in turn, can help produce cost-effective SCC mixes for practical application.

Hassan et al. 2008 conducted an experimental investigation to investigate the shear strength in addition to the cracking behavior of full-scale beams made of SCC and normal concrete, (NC). The parameters that were considered during this study were the type/coarse aggregate content of the concrete, depth of beam, and the ratio of the longitudinal reinforcing steel. By taking the crack patterns, crack widths, loads at the first flexure/diagonal cracking, ultimate shear resistance, as well as failure modes, each concrete's performance in beams was evaluated. The study was based on shear behavior of 20 full-scale reinforced concrete beams, without shear reinforcement, constructed of SCC and NC. The results concluded that the concrete did not play a significant role in the crack width, crack height, crack angles, or the overall failure mode of the beam. However, the SCC beams did exhibit, in comparison the NC beams, a lower ultimate shear load. Also, the shear strength reduction was greater in deeper beams that had smaller longitudinal steel ratios. The lower shear strength of the SCC beams is due to the lesser aggregate interlock development, which is caused as a result of a lower quantity of coarse aggregate when compared to the NC. Therefore, the ACI equation is not particularly ideal here, and most importantly, the risk of over-prediction is higher for the SCC beams than the beams made of NC.

Another study by Hassan et al. 2008 shed light on corrosion of steel reinforcements that are embedded into the SCC beams and NC beams. Beams with a width, depth, and length of 400, 363 and 2340mm, respectively, were studied and monitored under an accelerated corrosion test. The beams contained epoxy- and non-epoxy coated stirrups. Several measurements such as the current measurements, half-cell potential readings, crack patterns and widths, chloride ion content, rebar mass loss, as well as diameter reduction were analyzed to investigate the properties of the concrete in rebar corrosion protection and durability. It was found, based on the tests, that SCC mixtures exhibited superior rebar corrosion protection in comparison the protection offered by beams made of NC. The cracks in the SCC beams easily spread and extended unlike NC beams. The breaking and spalling of the concrete cover of SCC beams was apparent, and took place even at places where the crack widths were smaller than the ones in the NC beams. This could have easily been due to the lower volume of coarse aggregate in the SCC beams which resulted in such inferior quality. When casting occurred from one end, along the length of the full-scale SCC concrete beams, a non-uniform behavior of properties was noticed. This led to a lesser quality of concrete at the far end because of the poor compaction and distribution. In turn, the concrete cover was observed to undergo severe corrosion and spalling away from the casting point. It was found that the difference between the SCC and NC mixes was only apparent when the tests were carried out on large-scale beams, unlike the small-scale cylinder specimens. Since the bleeding and segregation effect was significantly reduced in small-scale cylinders, the difference was much pronounced. Not only that, but also the casting technique used in small-scale cylinders yielded a greater quality of concrete than the technique for large-scale beams. This was especially true for the concrete around the embedded steel bars (in comparison to the more porous layer of concrete below longitudinal bars within the large-scale beams).

In another study carried out by Bouzoubaa and Lachemi (2000), incorporation of high volume fly ash in SCC mixes was investigated. They formulated nine SCC mixes as well as one control concrete. These mixes incorporated 40%, 50%, and 60% of Class F fly ash as a replacement of cement. Based on the results, in terms of the slump flow, all the mixtures (except one) had a value between the ranges of 500-700mm, which clearly points out their good deformability. As for the tests regarded stability, all mixtures performed well. It was noticed that as the fly ash content and water-to-cementitious materials ratio was reduced, compressive strength seemed to increase. Based on this reasoning, it was found that at no significant extra cost, a concrete with a 28-day compressive strength of 35 MPa could be replaced. This SCC would be flow able, having a slump flow of 500mm and a flow time of 3 seconds. Plus, this concrete is likely to be segregation-resistant, and resistant against the heat of hydration of cement which causes thermal cracking. This can have its disadvantages as well; the SCC might display high bleeding water, as well as long setting times. As for its design cost, it was made with 50% cement replacement by fly ash, and with a water-to-cementitious materials ratio of 0.45.

A study carried out by Hossain and Lachemi (2007) focused on the effects of top bar (of steel) in SCC. They grouped twelve concrete specimens of NC and SCC to test them. They embedded steel bars into the concrete in differing locations: bottom, middle, and the top of the specimen. For each embedded bar, the thickness varied. A pullout test was used to evaluate the bond strength of slip of each steel bar. For all specimens, the type of bond failure was caused by splitting. These test result values were compared with proposed values in the equations of the ACI 318 Code. Based on this comparison, in case of SCC, the location factor of the ACI Code should be increased. The results pointed out that for top bars of NC the local bond strength was 20% greater than the top bars of SCC. As for the bottom bars, there was mostly equality within the results.

Lachemi et al. (2005) investigated the bond strength of glass fibre reinforced polymer reinforcing bars in normal concrete and SCC. They utilized the pull-out test of 36 GFRP reinforcing bars (embedded in the concrete specimens) in this study. They took into account the different parameters for different specimens: type of concrete, bar location, and thickness of cover. They formulated two series consisting of the twelve specimens, and manufactured and tested each. Six of the specimens were made of SCC, while the remaining six were made from NC, hence the two series. For each of the specimen used in this study, three reinforcing bars were embedded into the concrete, which translates into the utilization of three pull-out tests for each specimen. All specimens failed because the concrete split, and no pull-out failed of the bars was observed. Based on the results it was clear that the type of bond failure was by the splitting of the concrete for all specimens. As for the bond strength of the bottom GFRP reinforcing bars, both the SCC and NC exhibited similar strength. On the other hand, the bond strength of the top bars was greater of the NC in comparison to its SCC counterpart.

3 EXPERIMENTAL PROGRAM

3.1 Introduction

Experiments were conducted at concrete and structural laboratories of Ryerson University to develop and evaluate the properties self consolidating concrete (SCC) mixtures incorporating metakaolin (MK) and silica fume (SF). In the first phase, tests were conducted to develop SCC mixtures and to assess fresh / workability properties (such as slump flow, slump flow time, L-box ratio, V-funnel time and segregation index of a range of concrete mixtures with different percentage of silica fume/metakaoline as replacement of cement. In the second phase, tests were conducted to determine hardened properties such as compressive and splitting tensile strengths of developed concrete mixtures. A total of twelve SCC mixtures were developed and evaluated in addition to a control SCC mixture without SF or MK.

3.2 Materials

3.2.1 Cement

Type GU (General Use), hydraulic cement in compliance with CSA A3001-03 (Type 10 normal Portland cement) was used. Chemical, physical and strength properties of cement are shown in Table 3.1.

Table 3.1- Chemical and Physical Properties of Cement

Chemical Analysis (%)	**Cement**
Loss on ignition LOI	2.02
Silicon dioxide SiO_2	19.80
Aluminum Oxide Al_2O_3	5.51
Ferric Oxide Fe_2O_3	2.49
Calcium Oxide CaO	62.93
Magnesium Oxide MgO	2.43
Sulfur trioxide SO_3	4.50
Tricalcium silicate C_3S	52.26
Dicalcium silicate C_2S	17.37
Tricalcium aluminates C_3A	10.39
Tetra calcium aluminoferritte CaO	7.57
Total Alkali	1.00
Free lime CaO	0.79
Physical Analysis	**Cement**
Residue 45 um [%]	10.02
Blaine [m^2/kg]	410
Air content [%]	7.79
Initial set [mins.]	113
Compressive strength [MPa] 1 day	19.41
Compressive strength [MPa] 3 days	30.35
Compressive strength [MPa] 28 days	41.47

3.2.2 Water

Clean drinkable water with a temperature ranging between 22 and 24°C was used.

3.2.3 Aggregate

The grading of coarse and crushed fine aggregates was conducted according to ASTM C 136 and their grain size distributions are tabulated in Table 3.2.

Table 3.2- Sieve Analysis of Coarse and Fine Aggregate

Sieve #		3/8"	0.265 "	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
Opening (mm)		9.5	6.7	4.75	2.36	1.18	0.6	0.3	0.15	0.075
% of passing		100	99.8	96.5	82.8	69.8	51.8	22.1	6	1.5
Standard specifications	Min.	100		95	80	50	25	10		
	Max.	100		100	100	85	60	30	10	3

Table 3.3 shows the specific gravity, bulk density, moisture absorption, and surface moisture content of coarse and fine aggregates determined as per ASTM standards.

Table 3.3- Physical Tests of Coarse and Fine Aggregate

Test	Coarse Aggregate	Fine Aggregate
Dry loose bulk density, kg/m^3	1684	1730
Specific gravity (SSD), kKg/m^3	2671	2714
Specific gravity (Bulk). Kg/m^3	2638	2670
Moisture absorption. %	1.2	2.1
Fineness Modules		2.92

3.2.4 Super Plasticizer (SP)

PS-1466 from BASF Construction Chemicals (Master Builders) was used as SP. PS-1466 is based on polycarboxylate base and meets ASTM C 494/C 494 M requirements of Type A, water reducing; and Type F, high range water reducing, admixtures. Table 3.4 shows characteristics of PS-1466 as per the producer.

Table 3.4- Super Plasticizer PS-1466

Color	Brown
State	Liquid
Odor	No data
pH	2.7-6.5
Boiling point	100°C
Freeze Point	0° C
Specific Gravity	1.104-1.116

3.2.5 Metakaolin

Metakaolin can be used in combination with hydraulic cement for proportioning SCC mixtures. It should meet the requirements of ASTM C 618 or ASTM C 989. Metakaolin used for the development of SCC mixtures has the properties listed in Table 3.5.

Table 3.5- Chemical and Physical Properties of Metakaolin

Chemical Analysis (%)	Metakaolin
Silicon dioxide SiO_2	52.1
Aluminum Oxide Al_2O_3	41.0
Ferric Oxide Fe_2O_3	4.32
Calcium Oxide CaO	0.07
Magnesium Oxide MgO	0.19
Sodium Oxide Na_2O	0.26
Potassium Oxide K_2O	0.63
Loss on ignition	0.6
Specific surface area (m^2/Kg)	12,000

3.2.6 Silica Fume

Silica fume used in this project meets the requirements of ASTM C 1240. The chemical oxide composition of silica fume (wt %) is given in Table 3.6.

Table 3.6- Chemical Properties of Silica Fume

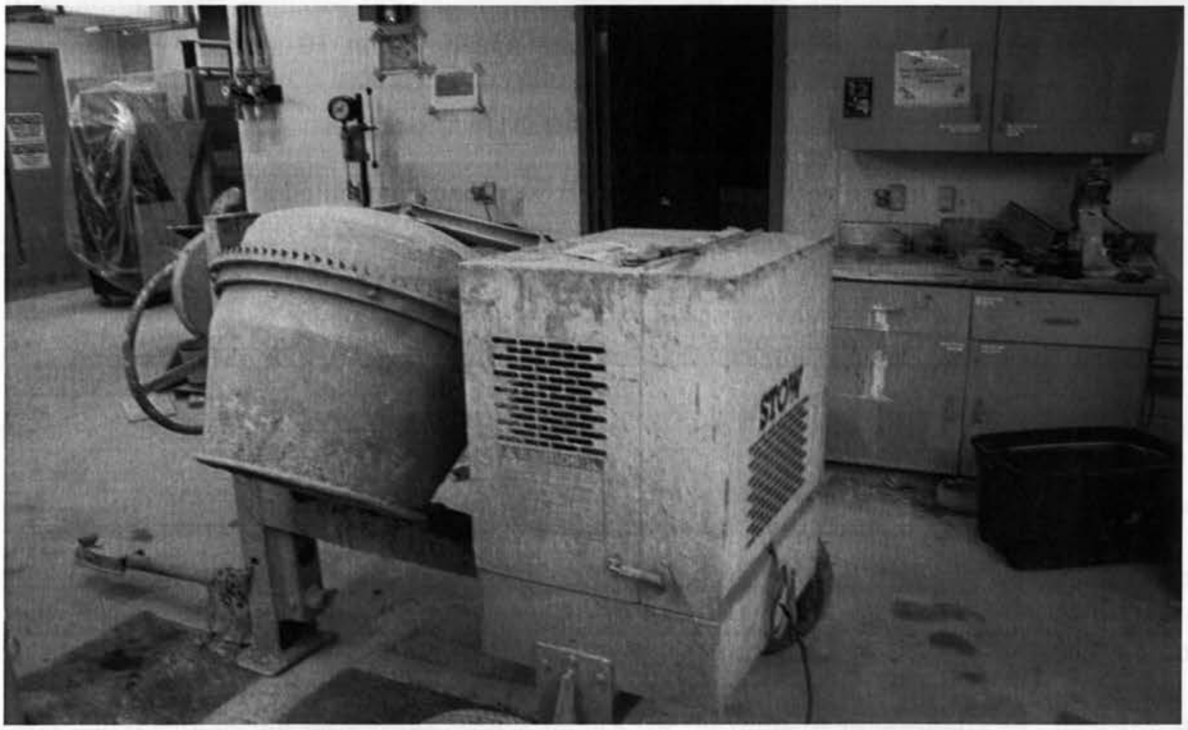
Chemical Analysis (%)	Silica Fume
Silicon dioxide SiO_2	92.26
Aluminum Oxide Al_2O_3	0.89
Ferric Oxide Fe_2O_3	1.97
Calcium Oxide CaO	0.49
Magnesium Oxide MgO	0.96
Sodium Oxide Na_2O	0.42
Potassium Oxide K_2O	1.31
Sulphur Tri Oxide SO_3	0.33

3.3 Methodology

3.3.1 Mix Preparation

A mobile concrete mixer without hoper consisting of a smooth steel drum with two paddles operated by an electrical 4.0 hp motor was used (Figure 3.1). A programmed Excel sheet for mix design was used to adjust and to calculate the amount of each of ingredients of concrete mixtures for each batch. The water requirement of the mix was carefully adjusted by balancing the water absorption of both coarse and fine aggregates.

Figure 3.1- Concrete Mixer



Before mixing, all required materials were prepared and weighed as per batch requirements. A small electrical scale was used to measure super plasticizer. All testing equipments to conduct slump flow, L-box, J ring and V funnel were prepared. The moulds for casting specimens such as prisms, cylinders and beams were also made ready.

3.3.2 Mixing Procedure

The mixing procedure involves the following steps:

1. After starting mixer, coarse and fine aggregate were added into drum and homogenized for 30 seconds.
2. Cement and SCM (SF or MK) were then added within 10 seconds of stopping period and then mixing continued for 30 seconds.
3. 60% of water mixed with super plasticizer was then distributed all over the mix and mixing continued for 30 seconds.
4. Remaining 40% of water mixed with super plasticizer was added and mixed for 60 seconds.
5. Stop and rest for 30 seconds.
6. Starting again the mixer and dispersion by hand gradually over concrete mix within 60 seconds.
7. Mixing continued for additional 120 seconds and then stopped.

3.3.3 Specimens

Immediately after concrete mixing, slump flow test followed by L-box, V funnel, J-ring and segregation index were conducted. Cylinders (100 mm diameter × 200 mm height) were cast without any compaction for strength testing. Cylinders were covered by wetted burlap and later shifted into 95% humidity room with 24 ±2°C. Cylinders were released from moulds after 24 hours, investigated visually and then kept in a humidity room until the specified testing time of 7 and 28 days.

3.4 Fresh Property Tests

Workability tests included the determination of slump flow diameter (spread), slump flow Time (T_{500}), segregation index, L-box ratio, J ring and V-funnel flow time.

3.4.1 Slump Flow

One of the most common tests performed to compare the lateral flow and the filling potentials of various SCC mixtures includes the slump flow test. Usually, the range of the slump flow is from 18-30 inches (or 450-750 mm). In production, this test allows for the assessment of the consistency of the SCC and for determining its capacity to deform under its own weight. As outlined by the ACI Committee Report 237R-26, the difference from each batch should not be greater than 2 inches (or 50 mm). It is normally the measure of the time it takes for the concrete to spread a distance of 500 mm, as well as the diameter of the concrete patty once it ceases to spread. Figure 3.2 shows the slump flow test performed during experimental program.

Figure 3.2- Slump Flow Test

Although not mandatory, the appendix of the ASTM C1611 / C1611M - 05 Standard Test Method for Slump Flow of Self-Consolidating Concrete outlines a procedure that can be used for the relative measurement of the properties of the SCC mix (such as its viscosity, stability, and flow rate). Calculations for the flow rate are carried out based on the duration of time it requires for the concrete to reach a diameter of 20 inches (or 500 mm). The viscosity of the concrete also has a direct impact on its flow rate. As for its stability, a visual inspection and examination of the concrete can hint any segregation.

Conventionally, a slump test has been used to determine the plasticity of the fresh concrete. However, since that test is not suitable for the analysis of the fluidity of the SCC, a slump flow test is used. The slump flow test provides a measure of its flow ability. The slump flow test, equipment-wise, is carried out similarly in the same manner as the slump test. The apparatus involved during the test include a regular slump cone, as well as a steel plate measuring 900 mm by 900 mm. These apparatus allow for the measurements of the two results of the test as mentioned above. The slump cone through which the concrete passes can be either used same up or inverted. Before commencing, the cone is raised, and without the use of any external forces or mechanical agitation such vibration or tamping, a sample of a fresh SSC mix is poured into the cone. Once through, the cone is lifted away and the concrete is left to spread without hindrance.

The time it takes to spread 500 mm is measured meanwhile. After the mix settles and the spreading stops, two perpendicular diameter measurements are taken of the concrete patty. It is important to note that if the two measurements have a difference of greater than 2 inches (or 50 mm), the test is to be deemed invalid and is to be repeated. The average of the two, which is rounded to the nearest half inch, can be concluded as the slump flow. As mentioned earlier, slump flow rates between the ranges of 24-19 inches are acceptable, while the minimum value for classification as an SCC is 20 inches (or 560 mm). Based on the test measurements, the SCC can then be classified as a Class 1, 2, or 3. As European Guidelines for self compacting concrete (EFNARC 2005) outlines, for an SCC mix to be recognized as Class 1, it must have a slump flow diameter of 550-650 mm, and the time it takes to spread 500 mm (T_{500}) of less or equal to two seconds. As for class 2, the slump flow diameter can be 600-750 mm, and T_{500} of greater or equal to two seconds. While EFNARC suggests the slump flow diameter of 760-850 mm for Class 3, no specification has been given for T_{500}.

3.4.2 Slump Flow with J-Ring

A J-ring test is similar to the slump flow test and is often used in conjunction. This test, however, helps determines the passing ability, which is the ease with which the concrete is able to pass through the reinforcing bars, which in this case is the J-ring. The apparatus needed includes the regular slump cone, a steel plate, and the J-ring. The J-ring consists of a thick metal ring, 1 inch (25.4 mm) wide and ½ inch (12.7 mm) thick. The ring has a central diameter of 12 inches (305 mm), and holds sixteen 5/8 inch (15.875 mm) bars below, spaced evenly, through which the concrete passes. The bars touch the ground with the ring above. The ring and the cone are used in conjunction.

Similar to the slump flow test, before commencement, the inverted cone is placed on the steel plate, and is to be concentrically in the J-ring. Now the sample of freshly mixed SCC is placed in the cone in one lift, and is not to be consolidated, neither should any mechanical agitation be applied. Once the concrete passes through, the cone is raised away from the ring and put away. The concrete is left to settle and spread as it passes through the J-ring bars. The average of two diameters of the resulting spread measured perpendicular to each other is reported as the J-ring flow of the concrete. The slump flow measured with the J-ring is shown in Figure 3.3.

Figure 3.3- J-Ring Slump Flow Test

The two measurements from the two different tests with a difference of less than one inch (or 25 mm) are considered very well, and indicate a good passing ability. On the other hand, if the difference is greater than two inches (or 50 mm), the passing ability of the concrete is considered to be not well. In 2002, EFNARC reduced the maximum acceptable value to 0.4 inches (or 10 mm). This method for the determination of a concrete's passing ability is suitable for the laboratory, as well as in the field.

3.4.3 L-Box

L-box test is an alternative to the J-ring test often used in developing SCC mixtures. It is also used to determine a concrete mixture's pass ability, fluidity, as well as the tendency to segregation. During this test, conditions that of the casting process are simulated as, under static pressure, the concrete is forced to flow through reinforced bars. The apparatus, L-box, is, simply a L-shaped device. It comprises of a "chimney" section and a "channel" section. The test performed is shown in Figure 3.4.

Figure 3.4- L-Box

Test

Although there are no certain guidelines as outlined by the EFNARC, the time it takes for the SCC to reach 400 mm from three steel bars, T_{400} can be measured by using the height of the concrete in the chimney, h_1, and the height of the concrete in the channel section, h_2, though it has been used previously to estimate an SCC's flow velocity. Upon commencement, the vertical section, the chimney, of the L-box is filled with 12 liters of concrete, and left to rest for one minute. Next, the gate at the bottom of chimney is lifted and the concrete is left to flow through the reinforcing bars, similarly to the J-ring test.

The self-leveling characteristic of the concrete can be calculated using the ration h_2/h_1. As the EFNARC guidelines suggest, the limit should be between 0.8 and 1.0, where above 0.8 is considered to be a good passing ability.

3.4.4 V-Funnel Test

The V-funnel test is a test used to evaluate the fluidity of an SCC, as well as determine the ability of the mix to pass through constricted areas and change its path. Using the apparatus the time it takes for the SCC to flow through the V-funnel is measured. As outlined by EFNARC, the SCC can be classified as class 1 if the time it takes it takes is less than 8 seconds, whereas class 2 for 9 to 25 seconds. Figure 3.5 displays V-funnel test.

Figure 3.5- V-Funnel Test

3.4.5 U-Box test

The U-box test can be used to determine the passing and filling ability of an SCC mix in a congested volume. In the test, a U-shaped box with two separate compartments is used. Between the two compartments, a small opening near the bottom allow for a concrete passage. A sample of fresh concrete mix is placed in one of the compartments and left to settle. The parameter measured during the test is mainly the height difference of the two compartments. According to the EFNARC, a difference of smaller than 30 mm generally represents a good passing and filling ability. Figure 3.6 shows the U-Box test performed in the laboratory.

Figure 3.6- U-Box Test

3.5. Mechanical Properties Tests

It should be noted that the concrete specimens were cast without any mechanical vibration or compaction energy. At least two specimens were tested for each of the hardened properties at standard ages. Test on cylinder compressive strength [ASTM C 39/ C 39M-01 2003] and splitting tensile strength of cylindrical concrete [ASTM C 496-96 1996] were conducted to determine the hardened properties of the concrete mixtures. The cylinder specimens and testing machine are shown in Fig 3.7.

Figure 3.7- Cylinder under Compression Failure and Testing Machine

3.5.1 Compressive Strength

Capped concrete cylinders (100 mm diameter with 200 mm height) made without compaction / vibration were crushed by compression machine at 7 and 28 days. The compression machine had a capacity of 400,000 lbs. Medium failure load, range 3 (up to 80,000 lbs) was used for all cylinders as per ASTM C 39/C 39 M-01 2003. Figure 3.7 shows the cylinders (100 mm× 200 mm) used for testing compressive strength.

3.5.2 Splitting Tensile Strength Test

The 7 days and 28 days splitting tensile strength of SCC was determined by using cylinders (100 mm diameter with 200 mm height) as per ASTM C 496-96 1996. The splitting tensile strength of the specimen is calculated by Eq. 3.1.

$$T = \frac{2P}{\pi l D} \qquad (3.1)$$

where

T = Splitting tensile strength (KPa)

P = Maximum applied load indicated by the testing machine (kN)

l = Length of cylinder (m)

D = diameter of the cylinder (m)

4 RESULTS AND DISCUSSION

4.1 Introduction

In this chapter, test results covering fresh (slump flow, flow time, and passing ability) and mechanical (compression and splitting tensile strength) characteristics of developed self compacting concrete with supplementary cementing materials (metakaolin and silica fume) will be described. Mix design details of developed SCC mixtures are presented. In addition, influence of SF and MK as replacement of cement on fresh and strength properties of SCC mixtures is also described.

4.2 Details of Developed SCC Mixtures

A total of 11 SCC mixtures were developed by using SF and MK as supplementary cementing materials. Four SCC mixes were developed by using different proportion of SF (3, 5, 8 and 11% of cement replacement) and six SCC mixes were developed by using different proportion of MK (3,5,8,11,15 and 20% of cement replacement) based on a control SCC mixtures (0% SF or MK). Tables 4.1 and 4.2 represent mix proportions of SCC mixtures with SF and MK, respectively, in addition to the control mix.

Table 4.1- Concrete Mix Proportion with Silica Fume

Component	0	SF 3*	SF 5	SF 8	SF 11
Silica Fume (%)	0	3	5	8	11
Silica Fume (kg/m^3)	0	13.50	22.50	36.00	49.50
Cement (kg / m^3)	450	436.50	427.50	414.00	400.50
Water (kg / m^3)	180	180	180	180	180
Water / binder	0.40	0.40	0.40	0.40	0.40
Sand (kg / m^3)	930	927.46	925.76	923.22	920.68
10 mm stone (kg / m^3)	900	897.54	895.50	893.44	890.98
Super plasticizer (L/m^3)	0	2.54	2.54	2.54	2.54

*Mix designation: SF represents silica fume and 3 represents % of SF

Table 4.2- Concrete Mix Proportion with Metakaolin

Component	0	MK 3*	MK 5	MK 8	MK 11	MK 15	MK 20
Metakaolin (%)	0	3	5	8	11	15	20
Metakaolin (kg / m^3)	0	13.50	22.50	36.00	49.50	67.50	90.00
Cement (kg / m^3)	450	436.50	427.50	414.00	400.50	382.50	360.00
Water (kg / m^3)	180	180	180	180	180	180	180
Water / binder	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Sand (kg / m^3)	930	928.64	927.74	926.38	925.02	923.21	920.96
10 mm stone (kg / m^3)	900	898.68	897.81	896.50	895.18	893.43	891.25
Super plasticizer (L/m^3)	0	2.77	3.08	3.08	3.34	4.11	4.23

*Mix designation: MK represents metakaolin and 3 represents % of MK

4.3 Fresh Properties

The results of slump flow (spread), slump flow time, J-ring, L-box, penetration test, U-box test and V-funnel flow time are summarized in Table 4.3. Results were evaluated according to "The European Guidelines for Self Compacting Concrete" [European SCC Guidelines, 2005]. The following table presents the findings based on the various fresh properties tests conducted.

Table 4.3- Results of Fresh Properties Tests

Mix No	Mix Designation	Slump Flow		J-ring			L-box		
		Final Dia (mm)	T_{50} (sec)	Final Dia (mm)	Diff in h (cm)	T_{50} (sec)	T_{20} (sec)	T_{40} (sec)	h_2/h_1
1	0	640±0	4.0	600±0	2.5	5.0	2.5	3.5	1.00
2	3SF	660±10	3.0	630±10	2.0	3.5	1.5	2.5	0.84
3	5SF	650±0	3.0	620±0	2.0	4.0	1.5	2.0	0.84
4	8SF	640±0	3.0	600±0	3.0	4.0	1.5	3.0	0.84
5	11SF	650±0	3.0	640±10	2.0	4.0	2.0	3.0	1.00
6	3 MK	650±10	4.0	650±0	2.0	4.0	2.0	3.5	0.91
7	5 MK	650±10	4.0	640±0	2.0	4.0	2.0	4.0	0.84
8	8 MK	640±10	4.0	650±10	2.0	4.0	2.0	3.5	0.84
9	11 MK	650±10	4.0	650±10	2.0	4.0	2.0	3.5	0.84
10	15 MK	650±10	4.0	640±10	2.5	4.5	2.5	4.5	0.91
11	20 MK	650±0	4.5	630±0	3.0	5.0	2.5	4.0	0.88

Table 4.3 Results of Fresh Properties Tests (Continued)

Mix No	Mix Designation	U-box test		V-funnel	
		T at stop flow (sec)	h_2/h_1	First T (sec)	T after 5 min (sec)
1	0	9.00	0.85	9.50	12.00
2	3 SF	6.00	0.89	6.00	7.50
3	5 SF	9.00	0.91	6.50	8.50
4	8 SF	8.00	0.86	7.00	10.00
5	11 SF	9.50	0.93	7.50	9.50
6	3 MK	9.00	0.82	8.00	10.00
7	5 MK	9.50	0.89	10.00	12.00
8	8 MK	9.00	0.89	10.00	13.00
9	11 MK	8.50	0.93	10.00	13.00
10	15 MK	11.00	0.89	11.00	14.00
11	20 MK	11.00	1.07	12.00	14.00

4.3.1 Slump Flow Test Results

All the SCC mixes were developed to have a slump flow of 650±10 mm. All mixes satisfy the criteria for SCC in terms of slump flow as per EFNARC. As shown in Figure 4.1, for constant dosage of SP, the SCC mix with a 3% silica fume concentration had the largest slump flow diameter, which suggests its high flow ability. In general, slump flow increased with the increase of SF (Table 4.3, Fig. 4.1). Higher dosages of SP was needed to keep slump flow of SK-based SCC mixtures at 650 mm, that suggested the decrease of slump flow with the increase of percentage% of metakaolin.

Figure 4.1 – Slump Flow of Various Mix Proportion

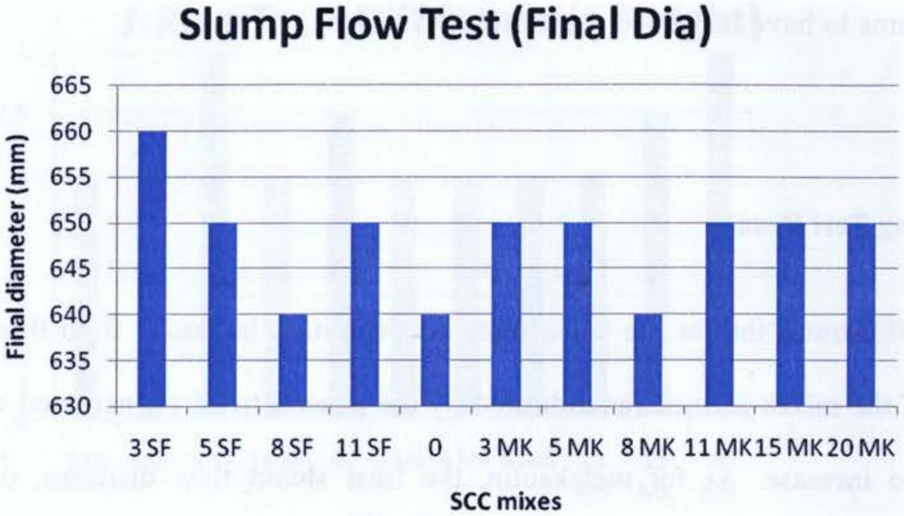
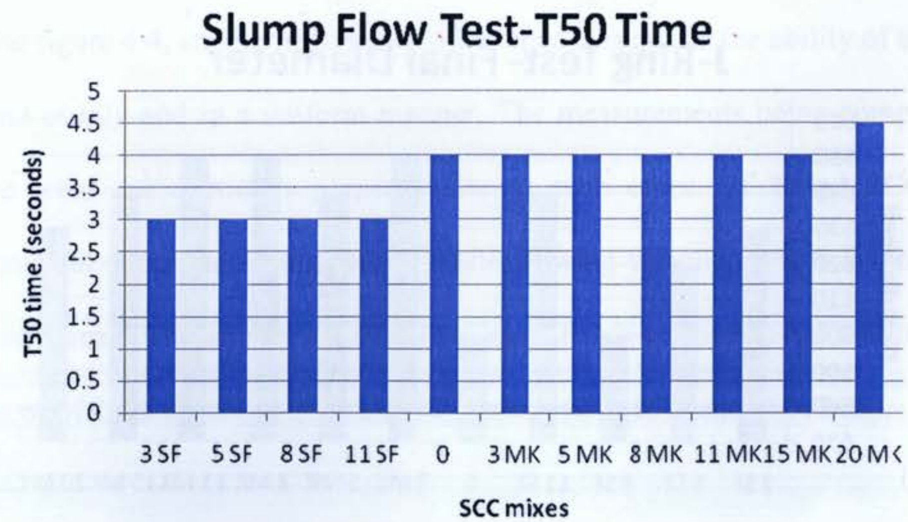


Figure 4.2 – Slump Flow T_{50}



The pattern, as seen in figure 4.2, seems very uniform. Mixes with silica fume reached a distance of 500 mm within 3 seconds, while the mixtures with metakaolin lagged behind at around 4 seconds although they had more or less similar slump flow. Based on this chart, silica fume clearly increases the workability of SCC, while metakaolin addition seems to have increased the viscosity and cohesiveness.

4.3.2 J-Ring Test Results

Figure 4.3 illustrates that as the silica fume concentration increased from 0 to 11%, the viscosity of the mixes seemed (as indicated by the general trend of increased slump flow diameter) to increase. As for metakaolin, the final slump flow diameter, on average, seemed to stay within the range of 630 – 650 mm.

Figure 4.3- J-Ring Slump Flow

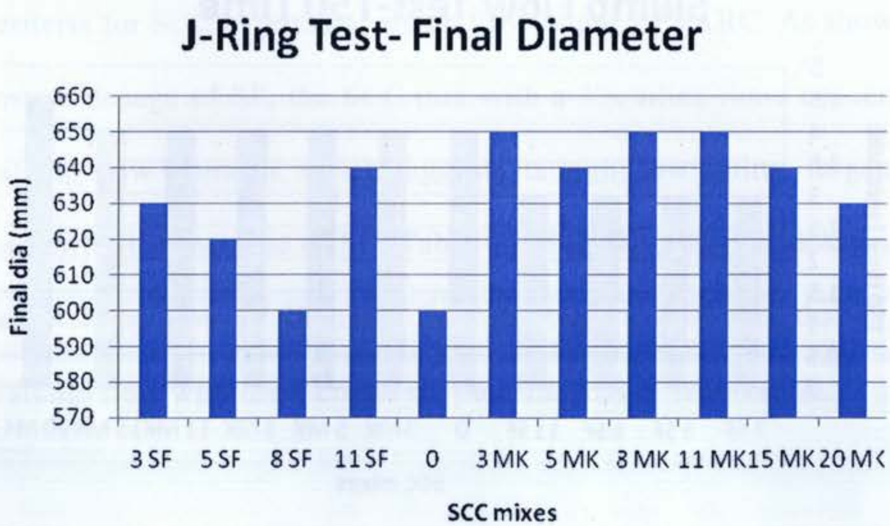
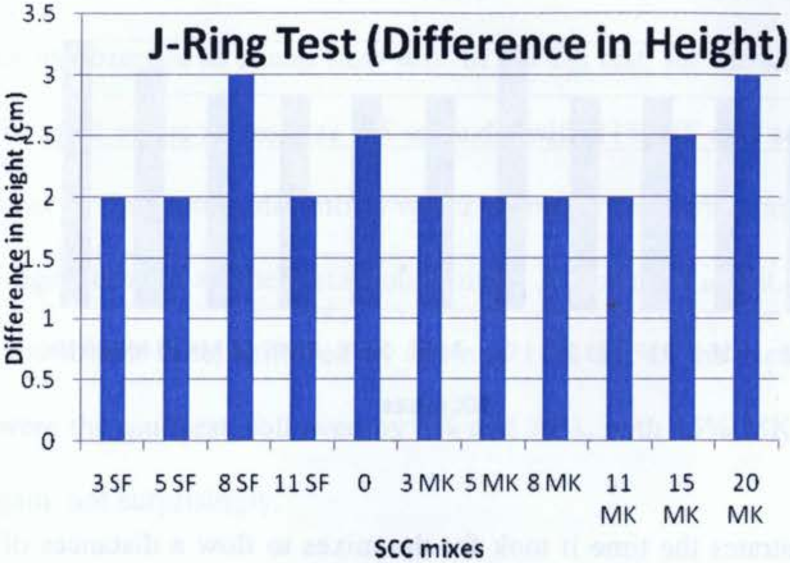


Figure 4.4- J-Ring Test (Diff in Height)



In the figure 4.4, smaller difference is better as it suggests the ability of the concrete to spread out evenly and in a uniform manner. The measurements being compared in the chart above were the diameters perpendicular to each other. SF based SCC mixtures exhibited uniform spread and consistency while flowing although 8% S.F mix did show some uneven spread. The uniformity of spreading out also seemed to have decreased with the increase of MK (as observed from the SCC mixes with 15% and 20% MK).

Figure 4.5 – J-Ring T_{50}

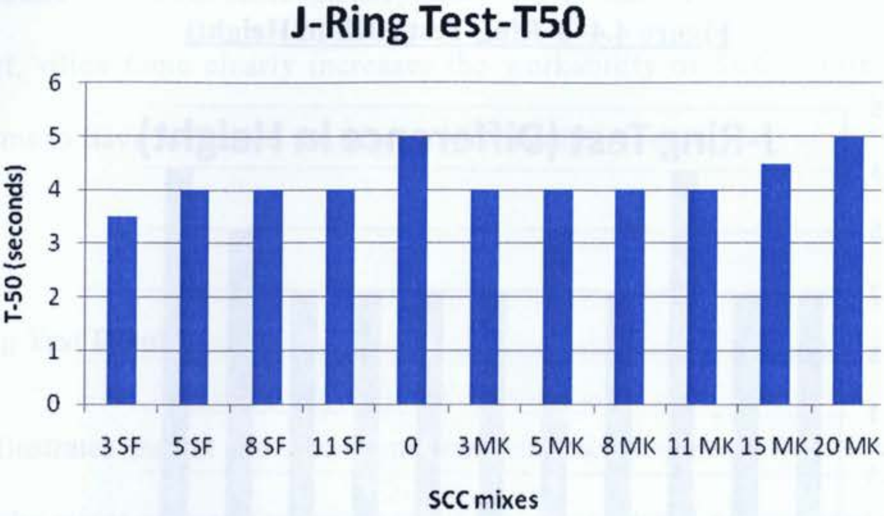


Figure 4.5 illustrates the time it took for the mixes to flow a distances of 500mm. The 3% silica fume mix had the least time, which is in accordance with the results of slump flow T_{50} test. The other mixes (except 15% and 20% M.K) had an average time of 4 seconds, which is still less than the time of the control concrete. Overall, so far these results suggest that addition of SF increases the flow ability while the addition of MK decreases the flow ability and increases the demand for SP to maintain a constant slump flow diameter. In addition, MK also increases the viscosity and cohesiveness of the mixtures.

4.3.3 L-Box Test Results

As evident in figure 4.6, the results of the T_{20} and T_{40} (times to reach 200mm and 400 mm in horizontal part of the L-box, respectively) present a similar influence of SF and MK on flow ability as observed in slump flow test. In the T_{20} test, for the silica fume SCC mixes, the time for most of the mixes was 1.5 seconds, with 11% SF at 2 seconds. Similarly, the time for most of the metakaolin mixes was 2 seconds. The 15% and 20% MK once again took the longest time of all the metakaolin mixes. As for the T_{40} test, the 3% and 5% silica fume had the lowest time, followed by 8% and 11% SF. In the metakaolin category, 8% and 11% were the quickest, followed by 5% and 20%, with 15% MK being the slowest of all once again, not surprisingly.

Figure 4.6 – L-Box Test

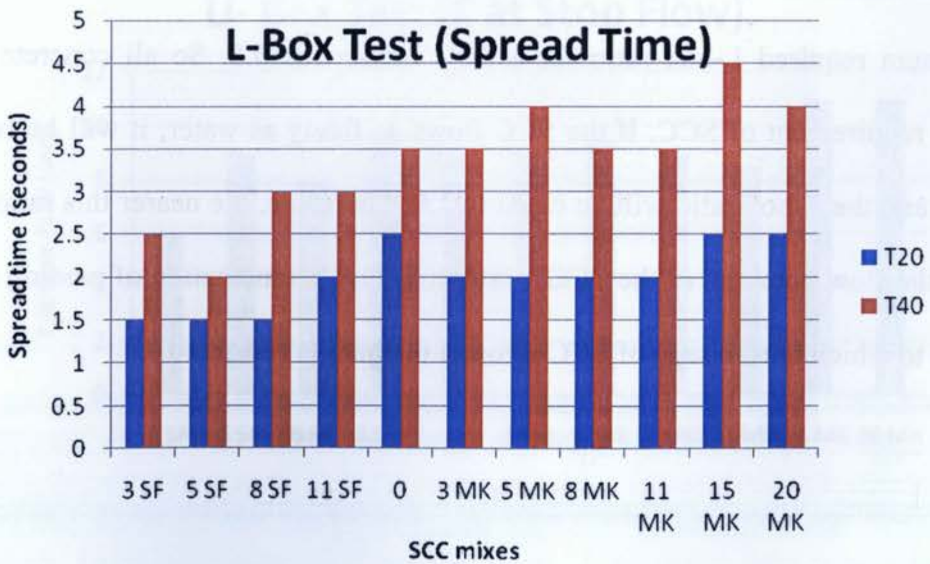
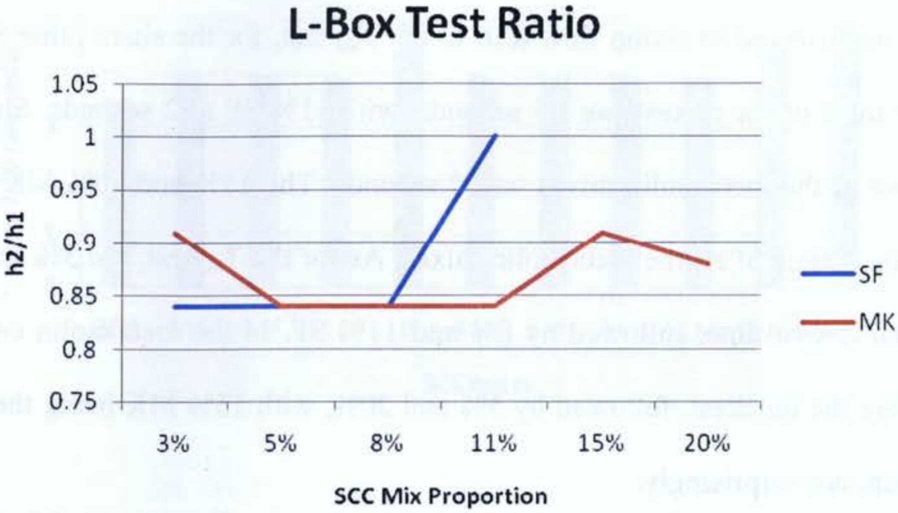


Figure 4.7 – L-Box Test (Ratio Between Heights)



It is clear from the results that all mixes had a L-box ratio of above 0.8 (Fig. 4.7). The minimum required L-box ratio for a SCC mixture is 0.8. So all concrete mixtures satisfy the requirement of SCC. If the SCC flows as freely as water, it will be completely horizontal and the L-box ratio will be equal to 1.0. Therefore, the nearer this ratio is to 1.0, the better the flow potential of the SCC mixture. This is an indication of passing ability, or the degree to which the passage of SCC through the bars is restricted.

4.3.4 U-Box Test Results

In order to justify the results of this test, they need to be compared to earlier tests, especially the tests regarding the diameter of the slump flow. Based on these comparisons, the 3% SF mix was the fastest to flow (with the lowest time 'T' required to flow in the U-box) as shown in the U-box test (Fig. 4.8). So, if the mix flows a great distance in short time (until it stops), one can classify it as a mix that has a high workability. Another example would be the 11%MK. In contrast, if a mix flows less distance in a greater time than the others, it can be considered the opposite. An example of this would be the 8%SF mix. For metakaolin mixes, "T" ranges between 9s and 11s.

Figure 4.8 – U- Box Test (T at Stop Flow)

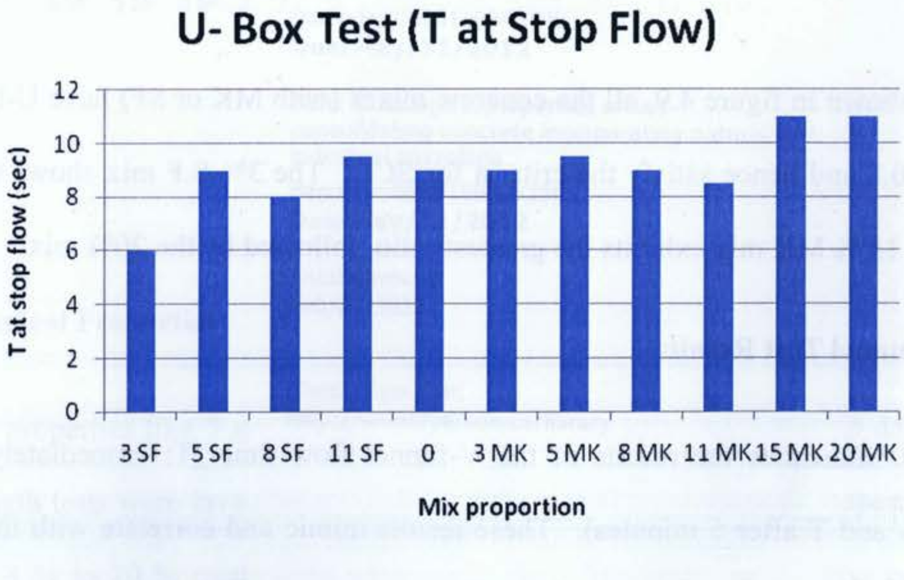
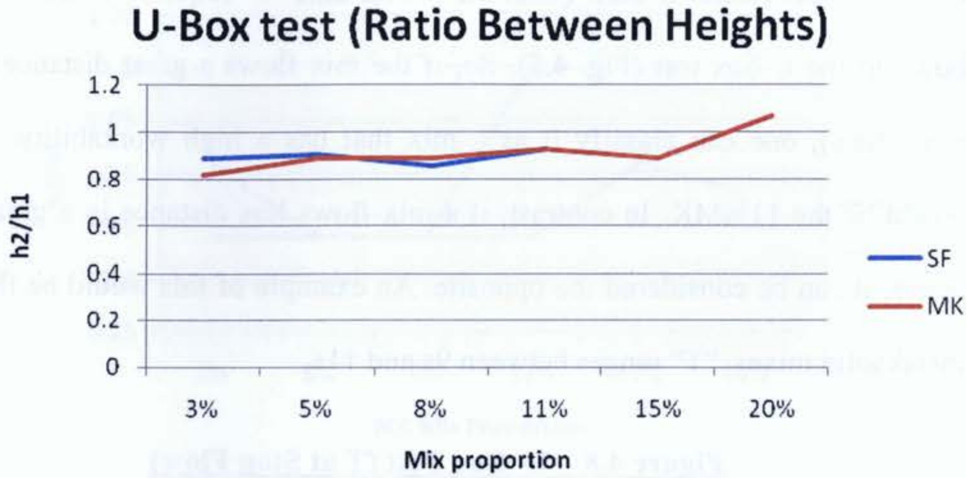


Figure 4.9 – U-Box Tests (Ratio Between Heights)

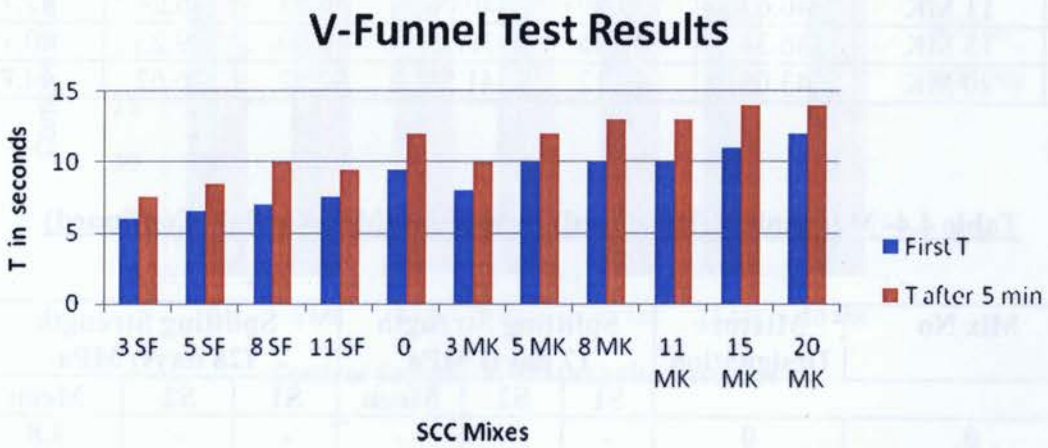


As shown in figure 4.9, all the concrete mixes (with MK or SF) have U-box ratio of more than 0.8 and hence satisfy the criteria for SCC. The 3% S.F mix shows the greatest ratio while 15 % MK mix exhibits the greatest ratio, followed by the 20% mix.

4.3.5 V-Funnel Test Results

Figure 4.10 illustrates the results of the V-funnel flow time (T: immediately after mix preparation and T after 5 minutes). These results mimic and correlate with the results in other tests. The viscous mixes, such as the 3% S.F, have the lowest time in either test. The pattern for the metakaolin mixes seems to be that as the concentration rises, the time in either tests increases with the increase of metakaolin (that exhibits higher viscosity and passing ability). The mixes with silica fume, in general, on the other hand, have low times compared to the metakaolin mixes. A maximum flow time of 12s was observed that is within the specified maximum 12s for a SCC mixture.

Figure 4.10 – V-Funnel Time



4.4 Mechanical Properties

Mechanical properties like 7 and 28 days compressive strength and 7 and 28 days splitting tensile strength tests were investigated. Table 4.4 presents the mechanical properties of SCC mixes with 3 % to 20 % metakaolin whereas Table 4.5 presents the 28 days compressive strength of SCC mixes made with 3 % to 11 % silica fume.

Table 4.4- Mechanical (Hardened) Properties (Metakaolin)

Mix No	Mixture Designation	Compressive Strength (7 days) MPa			Compressive Strength (28 days) MPa		
		S1	S2	Mean	S1	S2	Mean
0.	0	-	-	31	-	-	45
1.	3 MK	35.28	35.79	35.53	43.94	35.15	39.54
2.	5 MK	30.06	38.34	34.2	45.98	46.49	46.23
3.	8 MK	38.70	38.08	38.39	47.64	42.92	45.28
4.	11 MK	40.63	39.49	40.06	39.23	46.24	42.73
5.	15 MK	36.34	40.25	38.29	40.99	39.23	40.11
6.	20 MK	43.05	40.12	41.58	42.92	46.62	44.77

Table 4.4- Mechanical (Hardened) Properties (Metakaolin) (Continued)

Mix No	Mixture Designation	Splitting Strength (7 days) MPa			Splitting Strength (28 days) MPa		
		S1	S2	Mean	S1	S2	Mean
0.	0	-	-	-	-	-	3.8
1.	3 MK	2.7	3.21	2.95	4.08	3.24	3.66
2.	5 MK	2.7	3.18	2.94	5.28	4.20	4.74
3.	8 MK	4.55	3.97	4.26	3.00	3.69	3.34
4.	11 MK	3.24	3.53	3.38	3.66	2.73	3.39
5.	15 MK	3.85	2.60	3.22	4.63	4.19	4.41
6.	20 MK	3.82	2.57	3.19	3.42	5.01	4.21

4.4.1 Compressive Strength

Figure 4.11 presents the compressive strength of concrete mixtures with MK at 7 and 28 days. The 7 and 28 days compressive strength of control mix are 31 MPa and 45 MPa, respectively. The 7 day compressive strength of MK-SCC ranges between 34 MPa and 44 MPa. The 28 days compressive strength ranges between 39 MPa and 46 MPa.

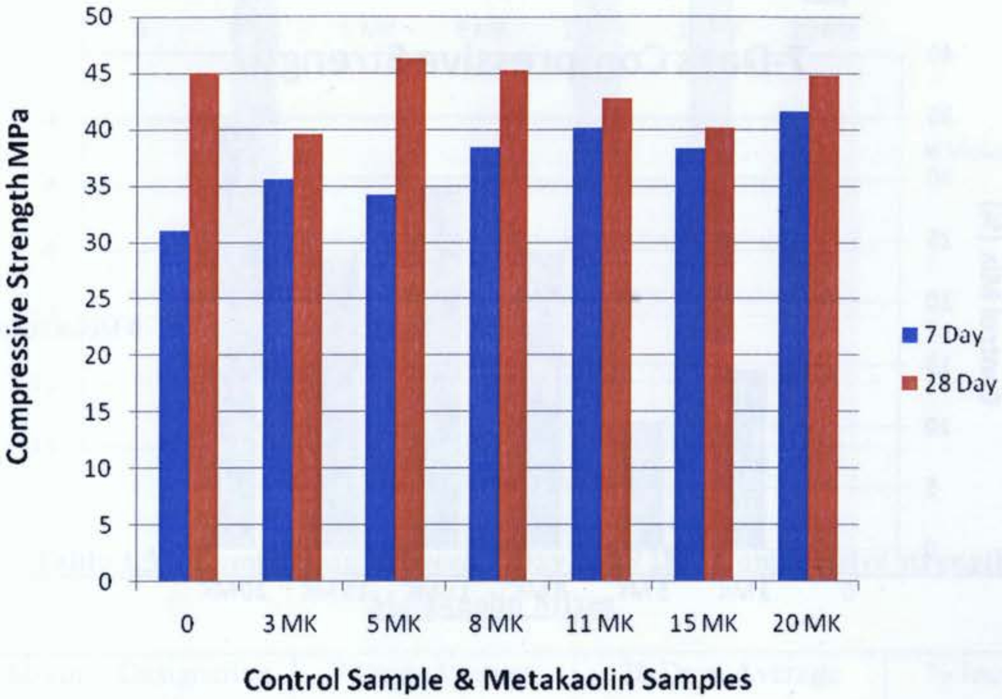


Figure 4.11 – 7 and 28 Day Compressive Strength of Metakaolin Samples

Figure 4.12 represents a comparison of the 7 day compressive strength of MK mixes and the control mix. Addition of metakaolin in various proportions from 3% to 20 % increased the 7 day compressive strength from 9% to 34 %.

Figure 4.12 – 7 Day Compressive Strength Gain or Reduction (MK Mixes)

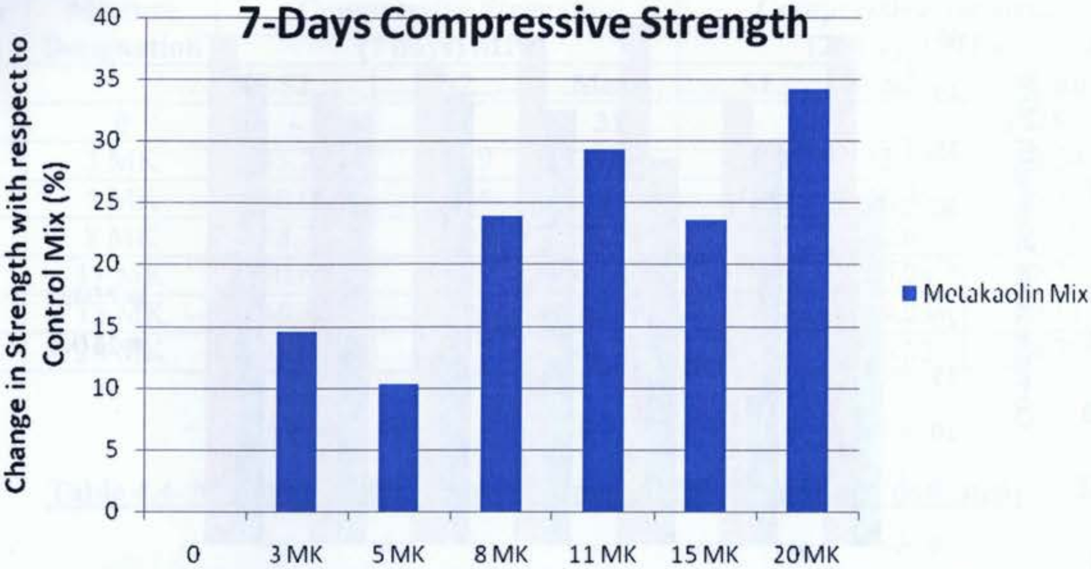


Figure 4.13 represents the comparison between 28 day compressive strength of metakaolin mixes (with various percentages of MK) to the control mix (0% MK). The result shows that 5% MK mix gains a strength of over 2% compared with that of control mix and 8% MK mix gains a very little strength of less than 1%. All other mixes show a decrease in compressive strength with respect to the control mixes and the decrease ranges between 1% and 12%.

Figure 4.13 – 28 Day Compressive Strength Gain or Reduction (MK mixes)

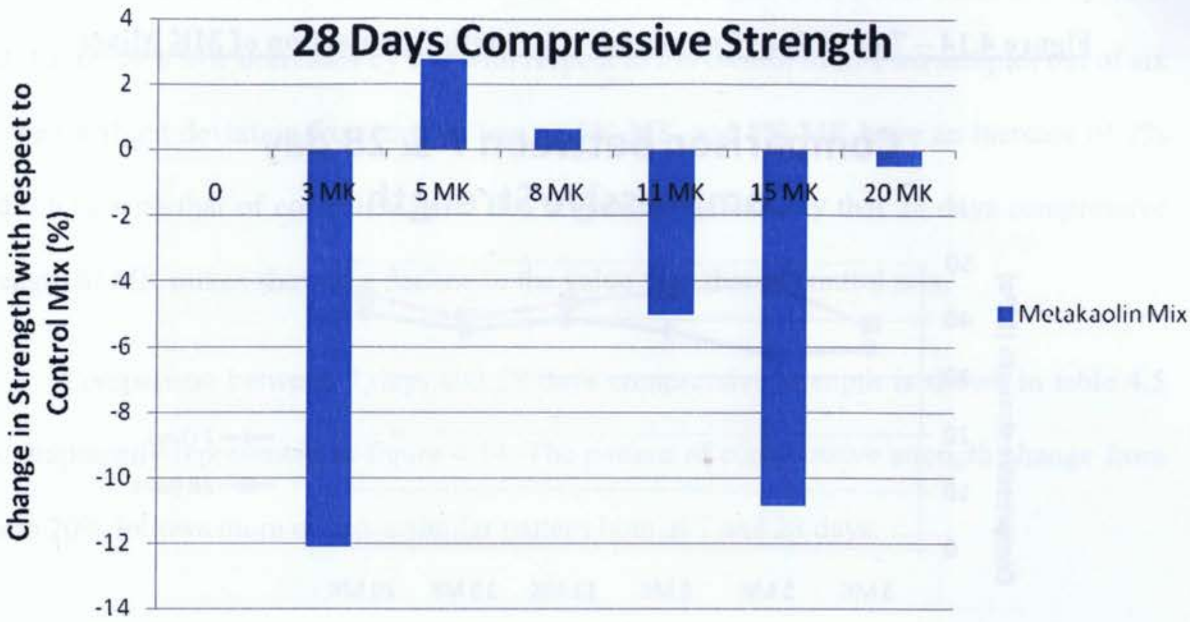
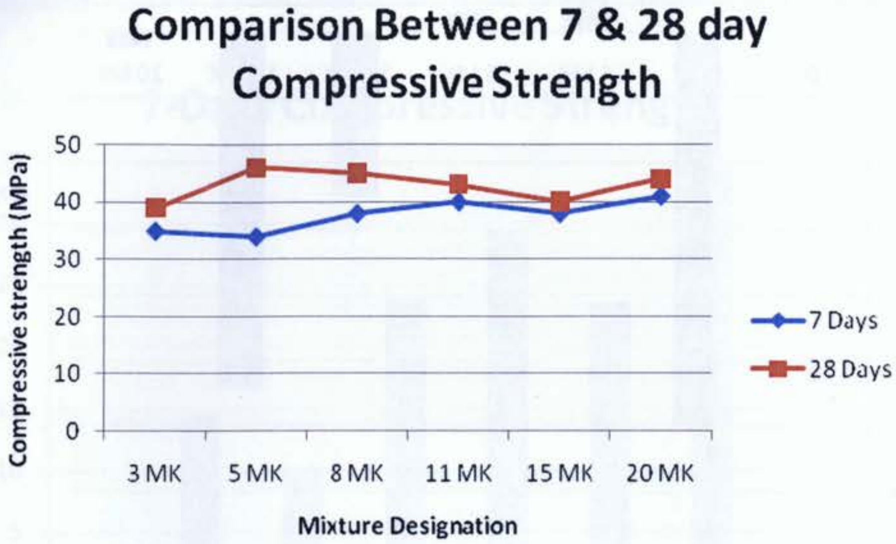


Table 4.5 – Comparison between 7 Day & 28 Day Compressive strength of Metakaolin Mixes

Mix No	Mixture Designation	7 Days Average Compressive Strength (MPa)	28 Days Average Compressive Strength (MPa)	% Increase
1.	3 MK	35	39	11
2.	5 MK	34	46	35
3.	8 MK	38	45	18
4.	11 MK	40	43	7.5
5.	15 MK	38	40	5.2
6.	20 MK	41	44	7.3

Figure 4.14 – 7 & 28 Day Compressive Strength Comparison of MK Mixes.



4.4.2 Comments on Compressive Strength Results of Metakaolin SCC Mixtures

The compressive strength test results of metakaolin samples are given in Table 4.4 and the comparison of 7 days and 28 days test results are enumerated in Table 4.5. Also the results are presented in Figures 4.11 to 4.14. It is observed that by increasing the proportion of metakaolin from 3% to 20% the 7 days compressive strength increases considerably (compressive strength of 3% MK is 14% higher than the control mix whereas 20% MK has 34% higher strength than control mix). This can be deduced that the early compressive strength of SCC mix increases as the proportion of metakaolin increases.

The 28 days compressive strength trend of MK mixes is a mixed one but in general the trend shows a decrease in strength. Compressive strength of 3% MK decreases by 12% and that of 20% MK decreases by 2% with respect to the control mix. Two samples out of six showed a slight deviation from this pattern as 5% MK and 8% MK have an increase of 2% and 0.6 % with that of control sample. But in general we can say that 28 days compressive strength of MK mixes showed a decline in the value than that of control mix.

Comparison between 7 days and 28 days compressive strength is shown in table 4.5 and graphically represented in figure 4.14. The pattern of compressive strength change from 3% to 20% follows more or less a similar pattern both at 7 and 28 days.

4.4.3 Compressive Strength of Silica Fume SCC mixes

Table 4.6 presents the 28 days compressive strength of SCC samples made with 3% to 11% silica fume. Figure 4.15 presents 28 days compressive strength of SF concrete mixtures. The 28 days compressive strength of control mix is 45 MPa. The 28 days compressive strength of SF mixes ranges between 37 MPa and 46 MPa. It is observed that most of the silica fume mixes have less compressive strength than the control mix. Samples ranging from 3% silica fume to 8 % have a gradual increase in strength with the increase of SF proportion whereas strength decreases at 11%.

Figure 4.16 represent the comparison between 28 days compressive strength of silica fume mixes (with various percentages of SF) to the control mix. The results show that only 8% SF mix gains strength of about 2% with that of control mix. All other mixes show a decrease in compressive strength with respect to control mixes that range between 8% and 16%.

Table 4.6 – Mechanical (Hardened) Properties (Silica Fume)

Mix No	Mixture Designation	Compressive Strength (28 days) MPa		
		S1	**S2**	**Mean**
0.	**0**	**-**	**-**	**45**
1.	SF 3	39.55	36.00	37.77
2.	SF 5	42.19	39.68	40.93
3.	SF 8	46.01	46.39	46.2
4.	SF 11	37.14	43.64	40.39

Figure 4.15 – 28 days Compressive Strength of Silica Fume Mixes

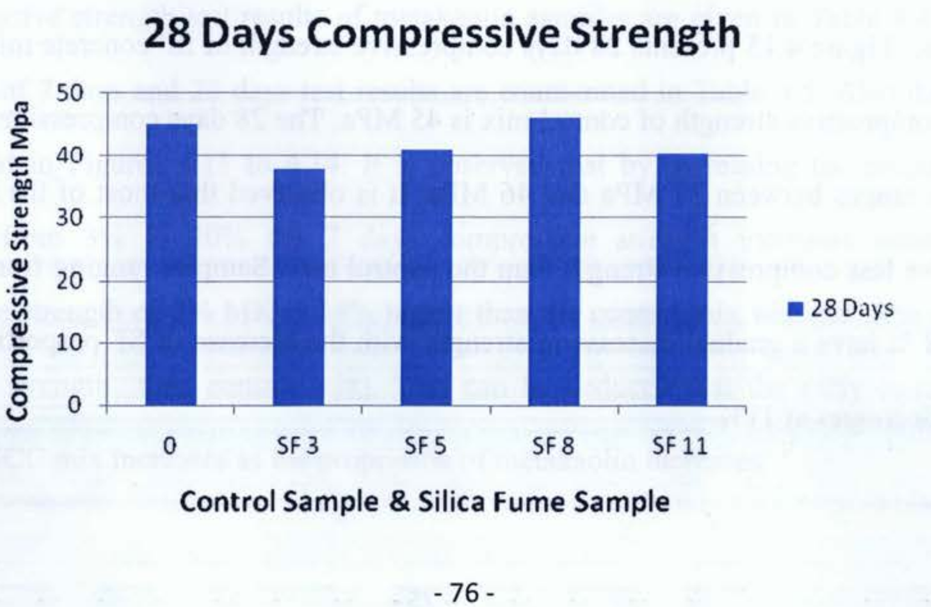
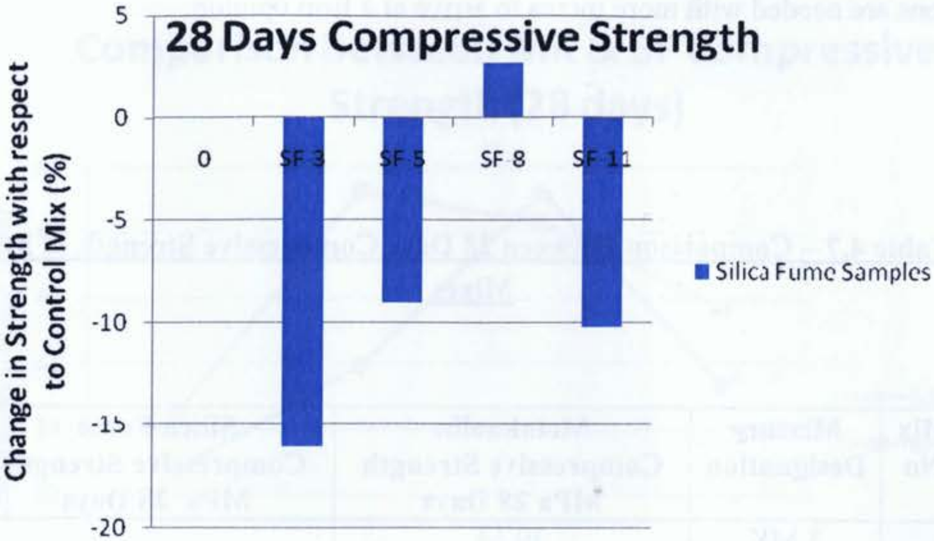


Figure 4.16 – 28 Days Compressive Strength Gain or Reduction (Silica Fume Mixes)



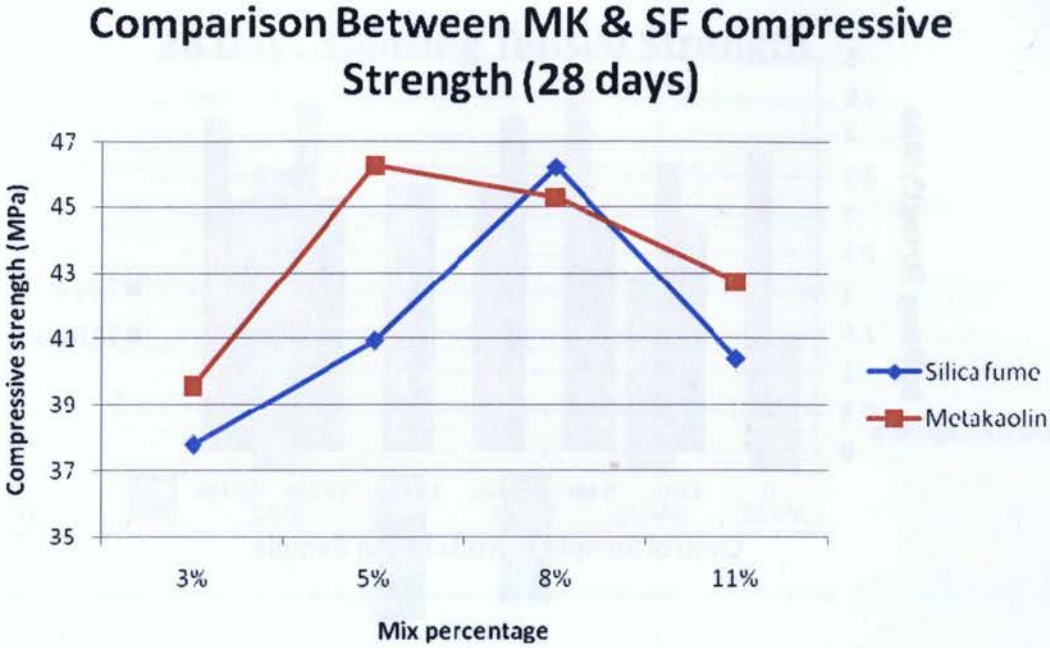
4.4.4 Comparison between MK & SF SCC Mixes

Table 4.7 presents compressive strength results of SCC mixes with equal proportion of SF and MK. Figure 4.17 shows the trend of compressive strength change in SF and MK based mixes. Values of SF mixes are low with respect to those of MK. But the interesting thing is that both types of mixes attain a maximum compressive strength of 46 MPa but with different proportion. Metakaolin attain this value with 5% whereas silica fume with 8%. It is observed that both samples gradually attain the maximum value of 46 MPa and then decreases with the increase of MK/SF beyond an optimum percentage Overall, compressive strength of MK mixes are greater than SF samples except 8% MK mix where we notice a decrease of 2% than SF sample. Otherwise 3% MK is 4.7%, 5% MK is 12.9% higher and 11% MK is 5.8% higher than respective SF mixes. We can deduce that higher compressive strength can be achieved by using metakaolin than silica fume in SCC. But more investigations are needed with more mixes to arrive at a firm opinion.

Table 4.7 – Comparison Between 28 Days Compressive Strength of MK & SF Mixes

Mix No	Mixture Designation	Metakaolin Compressive Strength MPa 28 Days	Silica Fume Compressive Strength MPa 28 Days
1.	3 MK	39.54	
1-a	**SF 3**		**37.77**
2.	5 MK	46.23	
2-a	**SF 5**		**40.93**
3.	8 MK	45.28	
3-a	**SF 8**		**46.2**
4.	11 MK	42.73	
4-a	**SF 11**		**40.39**

Figure 4.17 – 28 Days Compressive Strength of MK & SF Mixes



4.4.5 Splitting Tensile Strength

Figure 4.18 presents the splitting tensile strength of concrete mixtures with metakaolin at 7 and 28 days. The 28 days splitting tensile strength of control mix is 3.8 MPa as shown in Table 4.4. The 7 day splitting tensile strength ranges between 2.95 MPa and 4.26 MPa. The 28 days splitting tensile strength ranges between 3.34 MPa and 4.74 MPa. (Table 4.4)

Figure 4.18 – 7 and 28 Days Splitting Tensile Strength of Metakaolin Samples

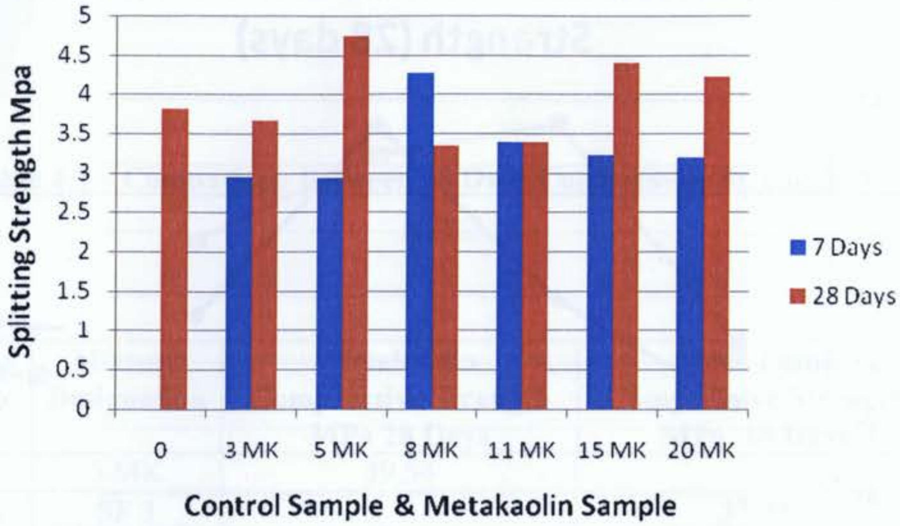
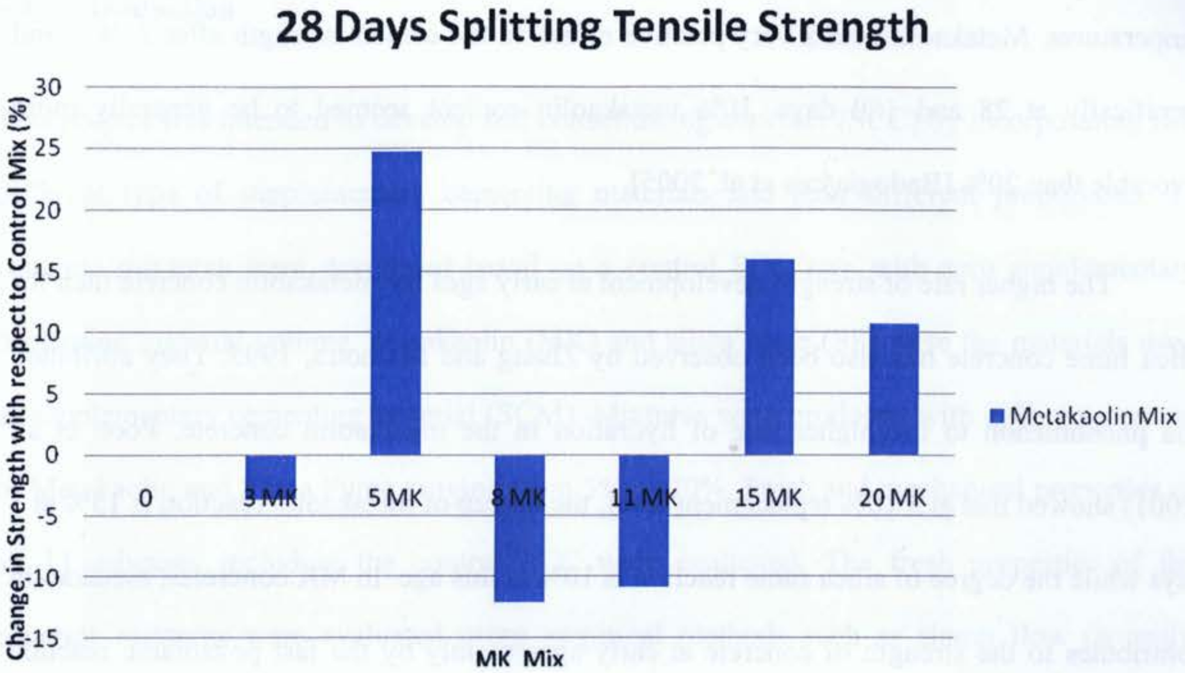


Figure 4.19 represents the comparison between 28 days splitting tensile strength of metakaolin mixes (with various percentages of MK) to the control mix. The result shows that 5%MK mix gains a strength of about 25%, 15% MK mix gains strength of about 15% and 20% MK mix gains a strength of about 10% compared with that of control mix. All other mixes show a decrease in splitting tensile strength with respect to control sample ranging from 3% to 12%. More investigations are needed on this aspect.

Figure 4.19 – 28 Days Splitting Tensile Strength Gain or Reduction (Metakaolin Mixes)



4.4.6 General Discussion of Mechanical Properties

Inclusion of MK as partial replacement of ordinary Portland cement (OPC) up to an optimum value enhanced the compressive strength of concrete. In our case we get high strength at 11% MK content. The optimum replacement level of OPC by MK to give maximum long-term strength enhancement was about 20% [Wild et al. 1996]. Brooks and Johari (2001) also reported that compressive strength increased with the increase in the metakaolin content. Similar results were also reported by Li and Ding (2003) where concrete achieved the best compressive strength with 10 % MK content. Poon et al. (2003) concluded that concrete containing MK (0 to 20%) shows a distinct pattern of strength gain and loss at elevated temperatures. Metakaolin had a very positive effect on the cement strength after 2 days and specifically at 28 and 180 days. 10% metakaolin content seemed to be generally more favorable than 20% [Badogiannis et al. 2005].

The higher rate of strength development at early ages for metakaolin concrete than for silica fume concrete has also been observed by Zhang and Malhotra, 1995. They attributed this phenomenon to the higher rate of hydration in the metakaolin concrete. Poon et al. (2001) showed that at a 10% replacement level, the degree of metakaolin reaction is 15% at 3 days while the degree of silica fume reaction is 10% at this age. In MK concretes, metakaolin contributes to the strength of concrete at early ages mainly by the fast pozzolanic reaction [Poon CS et al. 2001]. But in fly ash concrete, pozzolanic reaction is not the predominant strengthening mechanism at early ages. Fly ash contributes to concrete strength mainly by the pore filling effect and the enhancement of cement hydration that are more significant at lower w/b ratios [Lam et al. 2000].

5 CONCLUSIONS & RECOMMENDATIONS

5.1 Introduction

This project was intended to develop self consolidating concrete (SCC) by incorporating two different type of supplementary cementing materials and their different proportions. 11 concrete mixtures were developed based on a control SCC mix with zero supplementary cementing material volume. Metakaolin (MK) and silica fume (SF) were the materials used as supplementary cementing material (SCM). Mixtures were produced with different percent of Metakaolin and Silica Fume ranging from 3% to 20%. Fresh and mechanical properties of all 11 mixtures including the control SCC were evaluated. The fresh properties of the concrete mixtures were evaluated using empirical methods such as slump flow (spread), slump flow time T_{50}, L-box/ U-box passing ability, J-ring and V-funnel flow time tests as per standard specifications. In addition the mechanical properties such as compressive strength and splitting tensile strength tests were conducted and evaluated.

5.2 Fresh Properties

The ability of SCC mixtures to flow was evaluated using the slump flow test and the L-box /U-box tests. The slump flow for the various SCC mixtures varied between 600 and 660 mm. It should be noted that using recent developments in chemical admixtures, stable mixtures with low segregation and slump flows higher than 700 mm can be produced. Generally, the SCC mixtures exhibited good ability to flow through the rebar of the L-box. Desired L-box/U-box test results should have h2/h1 (L-box ratio/U-box ratio) >0.8. Results from the L-box/U-box for all SCC mixtures were greater than 0.8 and there was no blockage of flow for all mixtures. Based on slump flow, L-box, J-ring, U-box and V funnel tests, the self-consolidating properties for all mixtures were considered satisfactory.

5.3 Mechanical Properties

The compressive strength test results show that the metakaolin used in this study is superior to silica fume in terms of the strength enhancement of concrete. Among different replacement levels, the use of metakaolin at the replacement level of 11% performed the best, which resulted in the highest strength increase over the control concretes at all the test ages. However, the incorporation of silica fume increased the strength at the ages of or after 7 days. The higher rate of strength development at early ages for metakaolin concrete is attributed to the higher rate of hydration in the metakaolin concrete. They attributed this phenomenon to the higher rate of hydration in the metakaolin concrete. In MK concretes, metakaolin contributes to the strength of concrete at early ages mainly by the fast pozzolanic reaction. The developed MK based SCC mixtures (using 3% to 20% MK as replacement of cement) have 28-day compressive strength ranging between 40 and 46 MPa.

All of the SCC mixtures made by incorporating various proportions of SF and MK satisfies the criteria for SCC and hence are recommended for use in construction of different applications.

5.4 Recommendations for Future Research

A preliminary investigation is conducted to develop SCC mixtures by incorporating metkaloin as supplementary cementing materials. More investigations are needed and future research studies should be conducted on the following areas;

- Develop and optimize SCC by accommodating high volumes of metakaolin in wide range of mix proportion.
- Evaluate shrinkage, freezing and thawing characteristics, chloride/ sulphate resistance, fire durability and wear resistance of MK based SCC mixes.
- Develop standard specifications for MK based SCC by focusing on wide range of construction applications covering mix design, pump-ability, method of production and quality control.

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