Plastic and Hardened Properties of Self-Compacting Concrete

Kiavash Kandi

Submitted to the
Institute of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Master of Science
in
Civil Engineering

Eastern Mediterranean University
July 2025
Gazimağusa, North Cyprus

Approval of the Institute of Graduate Studies and Research

Prof. Dr. Ali Hakan Ulusoy
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science in Civil Engineering.

Assoc. Prof. Dr. Eriş Uygar
Chair, Department of Civil Engineering

We certify that we have read this thesis and that in our opinion it is fully adequate in scope and quality as a thesis for the degree of Master of Science in Civil Engineering.

Prof. Dr. Özgür Eren
Supervisor

Examining Committee

1. Prof. Dr. Özgür Eren
2. Prof. Dr. Khaled Hamed Marar
3. Asst. Prof. Dr. Saeid Kamkar

ABSTRACT

In recent years, addition of supplementary cementitious material (SCM) as a partial replacement to cement has widely increased. Utilization of Silica fume (SF) in self-compacting concrete (SCC) have demonstrated numerous advantages in terms of rheological and mechanical properties. This thesis describes experimental procedures related to silica fume self-compacting concrete having W/C of 0.5. It also investigates the impact of 3 different percentages (5, 7.5 and 10 %) SF as a substitute for cement on plastic properties of SCC by performing slump flow, J-Ring, V-funnel and L-box tests. Regarding the mechanical performance of SCC, compressive strength, splitting tensile strength, ultrasonic pulse velocity, Schmidt hammer test, flexural strength and absorption test were conducted.

Results from this study showed, increasing percentage of silica fume led to decrease in workability of SCC. Respecting the compressive strength values, rising SF percentage up to 10% caused improvement in performance of SCC, however, best performance was found to be incorporation of 7.5% silica fume in concrete. The results obtained from tensile and flexural values of SCC exhibited similar manners respecting strength enhancement. Moreover, increment of silica fume amounts decreased absorptivity and volume of permeable voids in concrete.

Keywords: self-compacting concrete, silica fume, workability, slump flow, compressive strength, flexural strength, splitting tensile strength, absorption.

ÖZ

Son yıllarda, çimentonun bir kısmının yerine yardımcı bağlayıcı malzemelerin (YBM) kullanımı giderek artmaktadır. Bu malzemeler arasında özellikle silis dumanı (SD), kendiliğinden yerleşen betonun (KYB) reolojik ve mekanik özelliklerini iyileştirmede önemli avantajlar sunmaktadır. Bu tez çalışmasında, 0.5 su/çimento oranına sahip silis dumanı katkılı KYB karışımları üzerinde yapılan deneysel çalışmalar sunulmaktadır. Çimentonun %5, %7.5 ve %10'u oranlarında silis dumanı ile değiştirilerek, taze beton özellikleri; çökme yayılması (slump flow), J-halkası, V-fünel ve L-kutu testleri ile incelenmiştir. Sertleşmiş betonun mekanik özelliklerini değerlendirmek amacıyla ise; basınç dayanımı, yarma çekme dayanımı, ultrasonik ses geçiş hızı, Schmidt çekici, eğilme dayanımı ve su emme testleri gerçekleştirilmiştir.

Elde edilen sonuçlara göre, silis dumanı miktarının artması KYB’nin işlenebilirliğini azaltmıştır. Basınç dayanımı açısından, %10’a kadar silis dumanı ilavesi beton performansını artırmış; ancak en iyi performans %7.5 silis dumanı kullanımında elde edilmiştir. Çekme ve eğilme dayanımı sonuçları da benzer şekilde dayanım artışı göstermiştir. Ayrıca, silis dumanı miktarındaki artışın betonun su emme kapasitesini ve geçirimli boşluk hacmini azalttığı belirlenmiştir.

Anahtar Kelimeler: kendiliğinden yerleşen beton, silis dumanı, işlenebilirlik, çökme yayılması, basınç dayanımı, eğilme dayanımı, yarılma çekme dayanımı, su emme.

DEDICATION

I allot this work to family members of mine who have been the definite source of encouragement and support during this program and my whole life. I have great feeling of gratitude towards my parents who have always inspired me to work smarter and harder. I also would like thank my siblings who have encouraged me permanently to pursue my goals.

ACKNOWLEDGMENT

First of all, I have gratitude towards my thesis supervisor Prof. Dr. Özgür Eren EREN, for his valuable feedbacks, infinite patience, constant guidance during the course of the thesis.

In addition, I show my gratitude to staffs especially, Mr. Ogün Kiliç who offered me help during conducting the experimental procedures of my thesis.

Last but not least, I have a deep sense of appreciation to all the staffs from Civil engineering department of Eastern Mediterranean University.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ACI	American concrete institute
C-S-H	Calcium silicate hydrate
CA	Coarse aggregate
FA	Fine aggregate
GGBFS	Ground Granulated Blast Furnace Slag
MOE	Modulus of elasticity
SCC	Self-compacting concrete
SF	Silica fume
SP	Superplasticiser
SCM	Supplementary cementitious materials
VMA	Viscosity modifier agent
WA	Water absorptivity
W/C	Water to cement ratio

Chapter 1

INTRODUCTION

1.1 Study Overview

In recent years, development of a type of concrete with extraordinary rheological and mechanical properties has been the main objective of most researches. Regarding the issue, incorporation of supplementary cementitious materials (SCM’s) in SCCs has widely investigated. Utilization of these chemical and mineral admixtures in concrete lead to improvement of workability and compressive strength. Silica fume (SF) is one of these SCM’s which contribute to better performance of concrete with respect to mechanical features and permeability. In addition, inclusion of superplasticiser (SP) as a water reducing agent in SCC produce more cohesive concrete with better capability of passing and filling the formwork. However, excessive addition of above-mentioned materials has harsh effect on concrete properties. Thus, proper mixing design of SCC would be the primary challenge of each and every study in this field (Frhaan et al., 2020).

Incorporation of SF in concrete has great impact on plastic behaviour and led to improved cohesiveness and little or no bleeding of concrete. In terms of hardened properties, studies showed better compressive strength, flexural strength and more durable SCC obtained while silica fume was added (Frhaan et al., 2020).

Inclusion of superplasticiser in SCC is mainly due to keeping the workability of concrete constant. It will also raise Modulus of elasticity, compressive and flexural strength and consequently, decrease the permeability (Frhaan et al., 2020).

Emerging modern construction technologies and increasing high rise buildings with complicated structural designs contributed to demand for type of concrete which has outstanding mechanical performance as well as workability in order to be used in congested reinforced members. Therefore, employing appropriate mixing design for SCC is critical in construction industry.

1.2 Problem Statement

The cement industry is one of the critical sources of industrial pollution. About 5–8% of carbon dioxide produced by human globally is related to cement sector. Fossil fuels are burned for production of cement. “Cement production can emit about 500,000 tons of sulfur dioxide, nitrogen oxide, and carbon monoxide annually”. Nowadays, cement industry is trying to develop much eco-friendly and sustainable concrete by utilization of SCM’s as a partial replacement to cement. Cement could be replaced by Silica fume in SCC up to 20% in order to produce environment-friendly concrete (Turk et al., 2013).

In complex structures with heavily reinforced members, SCC can be used due to its great flow ability especially; when vibration of concrete is not applicable. Regarding the productivity and cost efficiency SCC performs better than conventional concrete by reducing number of labourers and eliminating the vibrators (Frhaan et al., 2020).

In order to decrease the cost of concrete manufacturing, increase productivity of projects, and develop more sustainable and environment-friendly concrete with satisfying properties, supplanting the cement by silica fume in SCC is a viable solution.

1.3 Study Objectives

Producing a concrete which is less harmful to environment and provide the opportunity to decrease the construction cost could be vital for construction industry. Replacement of cement with silica fume in SCC would provide positive benefits regarding plastic and hardened characteristics of concrete. Therefore, major focus of this study would be evaluation of silica fume impacts on properties of self-compacting concrete.

The intended objectives of this thesis are accomplished by replacing cement by different weight percentages (5, 7.5, and 10%) with silica fume while maintain the W/C at constant rate of 0.5. Moreover, performing numerous tests with respect to rheological and mechanical properties of concrete in order to find out optimum inclusion of silica fume in SCC.

1.4 Outline of the Study

The thesis is composed of 5 chapters. Chapter 1 explains introduction, chapter 2 presents findings of similar researches and literature review. Chapter 3 gives details of experimental programs based on methods and specifications of standards. Chapter 4 demonstrates obtained results of the experiments. Chapter 5 recaps findings of the research and draws conclusions of thesis.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

The demand for technical methods to enhance the properties of concrete is increasing in modern construction technology. A viable option is removing the cement from mixtures partially and replacing it with supplementary cementitious materials such as silica fume. Employment of this technique help us to have more sustainable and eco-friendly concrete with great characteristics (Cheah et al., 2020).

Reduction in shrinkage of concrete and improvement in compressive strength and permeability of SCC was reported while chemical and mineral admixtures were introduced to mixtures. Inclusion of mineral by-products like quarry dust and silica fume in concrete provide solution to environmental issues with low cost (Dehwah, 2012).

Enhancement of self-compaction of concrete without incorporation of fine mineral admixtures is almost impossible. Durability properties of SCC was found to be better in comparison to normal vibrated concrete due to its homogenized and denser zone around the aggregates in concrete paste. Study by (Turk et al., 2013) showed increment in strength values, durability properties, and workability of concrete when mineral additives was introduced to mixtures. Incorporation of silica fume and super plasticiser together in concrete, made the self-levelling process of concrete more straightforward

(Smirnov et al., 2020) and also led to enhancement of quality and toughness of SCC by improving interface zone and producing calcium silicate hydrate (C-S-H) (Ofuyatan et al., 2021).

Silica fume was replaced up to 15% of cement weight in SCC mixtures which resulted in high strength concrete with better mechanical properties but decreased workability values (Kennouche.S, 2013).

2.2 Concrete Constituent

In concrete production, cement, water, fine and coarse aggregates along with mineral and chemical admixtures are incorporated. Concrete is composed of two major parts; paste and aggregates. The paste is typically made of cement, water, and admixtures. Self-compacting concrete consist of two primary admixtures. Firstly, chemical admixtures such as water-reducing agent and viscosity modifiers. Secondly, mineral admixtures and SCM's namely silica fume, fly ash etc. To produce SCC with considerable properties, high powder content about 450 to 650 kg/m^3 is needed. Therefore, addition of SCM's partially as a substitute to cement would provide advantages regarding the environmental pollutions and improvement in concrete performance. Study by (Pang et al., 2022) suggests replacement of cement by SF up to 10% while keeping the SP content steady at 1% of cementitious material weight in order to obtain desired SCC properties.

2.2.1 Self-Compacting Concrete

Self-compacting concrete was firstly introduced to construction industry by Japanese researcher in 1980's. In order to decrease number of skilled workers, concreting in congested reinforced areas, and improvement of mechanical properties of concrete, SCC was emerged in construction industry. Main asset of this type of concrete is its ability to spread under own weight in places that compacting act is not applicable (Frhaan et al., 2020).

SCC definition based on American Concrete Institute (ACI Committee 237, 2007); is a type of concrete which spread easily and create homogenous and durable concrete with great ability to fill the formwork in dense reinforced places without any need to external compaction. It also has almost same engineering properties as normal vibrated concrete. Moreover, British standard defines SCC as a concrete with capability of self-consolidation and spreading in cast and reinforcing areas evenly due to its own weight (Frhaan et al., 2020).

SCC was described as a type of concrete with great workability and flow ability in complicated structural elements which fills formwork uniformly without segregation. Thus, it is placed faster than normal concrete especially in complex reinforced members. In addition, it would decrease the total time and cost of construction to finish. (Dehwah, 2012) reported SCC as a concrete with considerable fluidity and pump ability which provide better quality concrete and safe working environment by reducing number of laborers and noise pollution caused by mechanical vibrator (Gesoğlu & Özbay, 2007).

Respecting production of SCC three methods are used. First powder type which consist of fine materials incorporation in concrete which are smaller than 0.125 mm. Second procedure is utilization of Viscosity Modifier Agent (VMA) in concrete in order to control workability and reduce probable segregation and bleeding. Last method is combined of first two methods (Vivek, 2021).

2.2.2 Silica Fume

Silica fume is categorized as a SCM with outstanding pozzolanic characteristic which is side-product of alloys consist of silicon during the process of electric arc furnace. Due to its fine particles and contribution excellent properties to concrete has gained popularity in modern construction industry. SF inclusion in concrete would improve mechanical and durability aspects and decrease segregation and bleeding in concrete by exploitation of its filler effect (Dehwah, 2012). The fine spherical particles of SF have diameter about 0.1 microns which increase physical characteristics of concrete due to their capability to fill voids between aggregates and cement paste to produce more cohesive concrete. process of SF production is seen in Figure 1 (Frhaan et al., 2020).

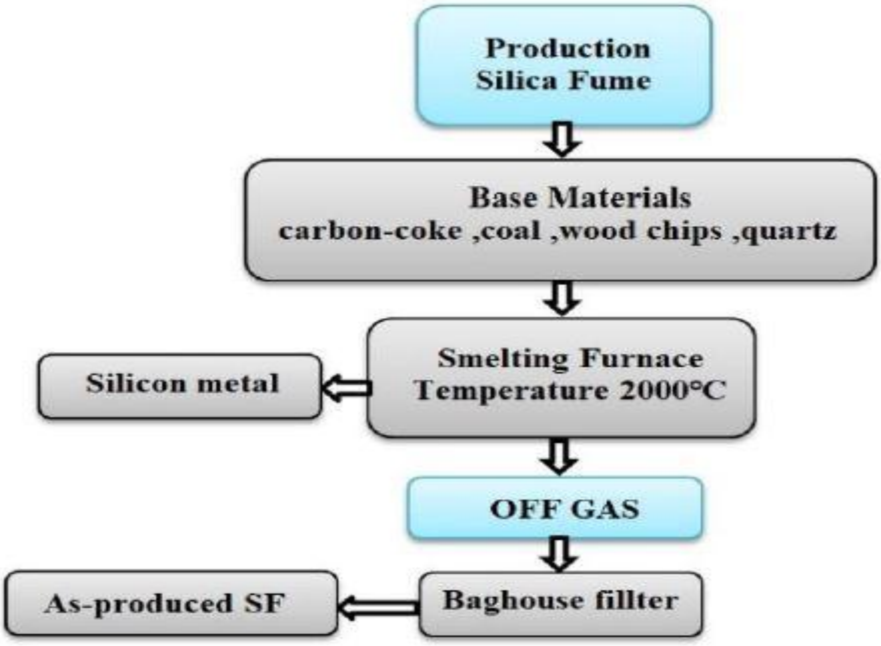

Figure 1: Silica fume manufacturing

2.3 Workability of Concrete

Cement, water and cementitious materials are components of cement paste which contribute to bind concrete ingredients together. Water plays imperative role regarding the workability properties of concrete. Chemical reaction between cementitious materials and water (hydration process) described by hardening the concrete. Water works as a lubricant among aggregates and make the concrete workable. Workability is a noticeable feature of concrete which can be defined by numerous properties such as flow ability, passing ability, finish-ability, and pumping ability of fresh concrete. W/C ratio and aggregate content affect the workability of concrete considerably (RILEM Technical Committee, 2006).

2.3.1 Effects of Silica Fume on Concrete Workability

SCMs have significant specific surface area which increase water absorption and reduce free water content in concrete. Thus, fineness and content of SCMs has huge influence on workability properties of concrete. Silica fume incorporation in concrete led to reduction in fluidity at fresh state (Pang et al., 2022). It was observed inclusion of SF in concrete changed the rheological behavior of concrete to thixotropic and increasing the SF has direct relation with viscosity of concrete (Benaicha et al., 2015). Results of slump flow and J-ring tests showed decline in workability of SCC whilst SF was introduced to mixtures (Lu et al., 2015). Respecting workability of SCC, disappointing performance was observed while silica fume was introduced in mixtures in comparison to other mineral admixtures. Increasing stability and reducing workability of SCC were concluded when SCMs were added (Benaicha et al., 2019). Influence of FA and SF on workability of SCC was investigated and results showed increasing silica fume content in concrete decreased the values related to workability characteristics (Gesoğlu & Özbay, 2007). Research was conducted to evaluate effects of zeolite, limestone, and silica fume on rheological behavior and workability of SCC. It was shown SF has the worst performance among these admixtures (Mazloom et al., 2018). In contrast, it was observed mixtures with silica fume escalated slump values up to 50 mm regarding the workability properties of concrete. When cement was replaced by 15% SF, 650-750 mm slump values were obtained which satisfied SCC requirement. However, another study revealed slump values of SCC with 10% SF was not within the range of standard specifications. (Frhaan et al., 2020) investigated 5,10,15, and 20% SF inclusion of binder weight and showed all SCCs performed well with respect to EFRANC standard (EFNARC, 2002) for fresh properties of SCC (Lisantono & Pratama, 2020).

2.4 Compressive Strength

One of the most crucial parameters to evaluate the mechanical properties of concrete is compressive strength. It is the concrete refusal to fracture under horizontal loading. It also can be defined as a maximum value that concrete area can tolerate under loading (Khayat & De Schutter, 2014). Study reported gaining strength at early ages in SCC is more noticeable rather than normal vibrated concrete. Compressive strength of SCC had almost 30% higher values compared to normal concrete. It could be due to improvement of microstructural behavior of SCC by adding fine powder admixtures which decrease the pores size (Nikbin et al., 2014). Effect of replacing cement by 15 and 30% by SF was examined. The results showed 15% substitution led to higher values of strength.

2.4.1 Impact of SF Inclusion on Concrete Compressive Strength

Increasing content of mineral additives in SCC led to increment in compressive strength values because of better and denser bond between aggregates and cement paste. (Turk et al., 2013) Stated that introduction of SF to concrete mixes eliminate the phenomenon of bleeding which led to increasing bond strength and compressive strength of concrete. (Frhaan et al., 2020) concluded increasing the content SF from 5 to 15% resulted in better performance of SCC (Mohammadi et al., 2015). Influence of SF and Quarry Dust on strength of SCC was studied and it was reported that concrete with 60 MPa compressive strength can be produced while SF was incorporated in SCC. Furthermore, silica fume mixtures contributed to almost 25% higher compressive strength. Based on study of (Dehwah, 2012) highest compressive strength values were obtained while silica fume was used in SCC compared to fly ash and normal SCC. Although, compressive strength of normal concrete found to be higher than admixture SCC at early age. Optimum silica fume volume regarding the compressive strength of SCC was reported at 20%. However, (Turk et al., 2013) claimed that 90 day-compressive strength of SCC raised up to 17% replacement of cement and gradually decreased to 20%. When cement supplanted by 15% SF, SCC gained maximum compressive strength about 90 MPa at 28 days. 28-day compressive strength of SCC decreased up to 31% compared to normal concrete when silica fume and recycled aggregate were incorporated in SCC production (Sasanipour et al., 2019). High strength SCC with compressive strength about 50 MPa was produced by utilization of 10 and 15 % SF in mixing proportions (Lisantono & Pratama, 2020). Maximum strength values with inclusion of 1-1.2% SP and 10-15% SF in SCC were achieved (Smirnov et al., 2020).

2.5 Splitting Tensile Strength of Concrete

The ultimate value of load that concrete tolerate to fail is called splitting tensile strength. Concrete is considered as a brittle material and has poor performance regarding the tension rather than compression. Excessive tensile load results in emerging cracks in concrete. Thus, identification tensile strength is among imperative hardened properties regarding the safety of structures.

2.5.1 Impact of SF Inclusion on Concrete Tensile Strength

Improvement in strength properties of SF-SCC was observed which is attributed to greater bond strength between concrete constituent due to excellent fineness of SF's granular powder (Alrawashdeh & Eren, 2022). Increment of SCC strength with 450 kg/m^3 binder content up to 33,8, and, 2% at 28, and, 90 days were observed when 10% silica fume was added (Jalal et al., 2012). In respect of tensile strength, among SCC mixtures with 5,10, and 15% SF inclusion, 5% was found to be optimum percentage of silica fume. However, all mixtures presented reasonable performance (Etli, 2023). The findings indicated that incorporation of 5% silica fume resulted higher strength in comparison to SCC mixes with 10 and 15% (Mahalakshmi & Khed, 2020). Simultaneous addition of 10% SF and 20% GGBFS to SCC contributed to 45.64% greater values of splitting tensile strength in comparison to conventional concrete (Vivek, 2021). Utilization of 10% SF along with different percentage of FA contributed to increment of SCC strength considerably (Yazıcı, 2008). Splitting tensile tests were performed on SCC with diverse volume of silica fume (2.5%,5%, and 7.5%). Although all the strength values were in same range, mixtures with 5% SF performed better (Bernal et al., 2018). Contrary to before-mentioned researches, it was declared that mixtures consist of SF had similar or even less tensile strength compared with normal SCC (Sharbatdar et al., 2020).

2.6 Flexural Strength

Flexural strength of concrete is described as capability of concrete to tolerate bending forces which are employed perpendicular to its longitudinal axis. Results of flexural test can be used to evaluate proportioning and uniformity of mixture for proper placement and construction of beams, slabs.

2.6.1 Influence of Silica Fume on Flexural Strength

Optimization of strength up to 40% was recorded while 10% silica fume was added to SCC (Pang et al., 2022). Respecting flexural strength, tests were performed on SCC with 10% SF at two different binder content of 450 and 500 kg/m3. Results exhibited increment in values of strength up to 58.9, 54 and 52%, 47, 50 and 52% at 7, 28 and 90 days respectively. Probable cause of this behavior could be due to even dispersion of silica fume fine particles in cement paste which contributed to improvement of bond strength by producing more C–S–H during the hydration process of concrete (Jalal et al., 2012). Replacing the concrete more than 15% namely; 25 and 35 % by silica fume showed huge decrease in amount of flexural strength of SCC (Ofuyatan et al., 2021). Based on flexural strength performance, inclusion of 15% silica fume in mixtures showed highest values of strength about 8MPa. Despite the fact that 10, 14, and 22% enhancement in flexural strength of SCC were obtained by incorporation of 5,10, and 15% SF respectively (Çelik et al., 2022). The impact of SF inclusion in fiber reinforced SCC was evaluated and it was noticeable that inclusion of 14% SF increased strength values about 35% (Mastali & Dalvand, 2016).

2.7 Water Absorption (WA)

The capacity of concrete to absorb water is considered as one of the major durability properties which is used to evaluate quality of concrete. (ASTM C642 − 21) defines water absorption of concrete as an increment in percentage of concrete weight when concrete is immersed in water after oven-drying the sample for distinct period of time.

2.7.1 Effect of Silica Fume on Water Absorption of Concrete

It was noted that inclusion of silica fume in concrete mixture played the most critical role in decreasing water absorption compared to other component of concrete (Raymond A et al., 2017). Increasing the amount of SF in self-consolidating concrete from 5 to 20% resulted in reduction in water sorptivity. It was also reported mixtures with SF absorbed less water in comparison to fly ash SCC (Turk et al., 2013). Impact of simultaneous SF and recycling concrete aggregate on absorptivity of SCC was studied and 41% decline in abosptivity values was reported (Sasanipour et al., 2019). Comparing absorption of water between mixtures with and without silica fume showed increment of absorptivity values up to 42.9% while SF was not incorporated in SCC mixtures (Sasanipour & Aslani, 2019). Assessment of water absorption in SCC whilst 15,25, and 35% of cement was replaced by SF exhibited WA values decreased up to 25% inclusion of SF and harshly increased afterwards (Ofuyatan et al., 2021). Studying impact of Silica fume addition by 5,10, and 15% of cement weight on WA properties of SCC was carried out. It was reported that by increasing amount of SF substitution, loss in WA values observed. 15% SF inclusion resulted in 20% decline in values of WA when compared to normal SCC (Etli, 2023). Increasing amount of SF in SCC led to reduction in coefficient of absorption. Optimal volume of SF addition to SCC was found to be 15% which led to decrease the WA by 38% (Çelik et al., 2022). Increment of SF percentages up to 20 resulted in decline of WA amounts by 18.5%. It could be due to increasing the specific surface of cement paste by incorporation of SF (Sharbatdar et al., 2020).

Chapter 3

METHODOLOGY

3.1 Introduction

The principal aim of this experiments is to examine the impact of SF addition by 5, 7.5 and 10% while keeping Gelenium superplasticizer at constant content of 1% of cement weight. Assessment of physical, mechanical and durability properties of SCC with diverse content of silica fume whilst W/C maintained at constant rate of 0.5 was primary goal of this study. To do so following tests were conducted:

- Slump flow test, J-ring test, L-box test, V-funnel test
- Compressive strength
- Split tensile strength
- Flexural strength
- Ultrasound pulse velocity
- Schmidt hammer test
- Water absorption test

This chapter describe properties of materials and technical procedure of experiments according to specific related standards.

3.2 Materials

Description of materials incorporated in this work is elaborated in upcoming parts.

3.2.1 Cement

Portland slag cement conforming to the TS EN 197-1 standard (CEM II/B-S 42.5 N) was incorporated. The characteristics of cement can be seen in Table 1.

Table 1: Chemical and physical characteristic of cement

oxide compound	
SiO_2	amount(%)
CaO	29.82
Al_2O_3	57.43
Fe_2O_3	5.88
MgO	2.47
$CaCO_3$	3.46
$MgCO_3$	-
SO_3	-
Free CaO	2.64
Specific gravity	1.09

3.2.2 Mixing Water

The concrete was produced and cured using tap water without any pollution, organic materials, oils, and alkalis.

3.2.3 Fine and Coarse Aggregates

limestone aggregate with 5 mm diameter (sand) was incorporated. Coarse aggregate particles have 10,14, and 20 mm diameters. Grading the aggregates was performed complying with ASTM C33/C33M-18 standard. Moreover, sieve analysis of aggregates conforms to ASTM C136M-19 standard. The results of sieve analysis for fine and coarse aggregates are depicted in Figure 2 and 3 respectively.

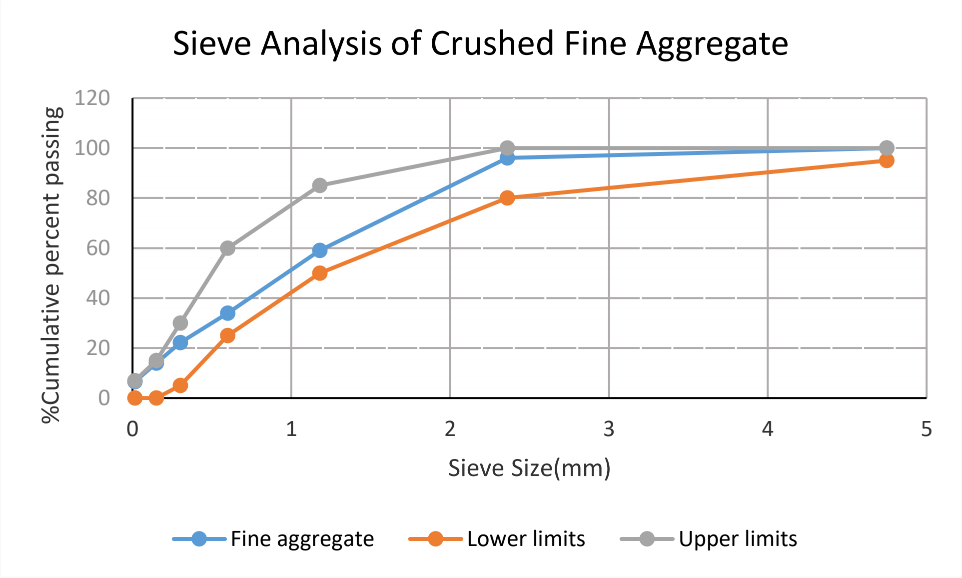

Figure 2: Fine aggregate (sieve analysis)

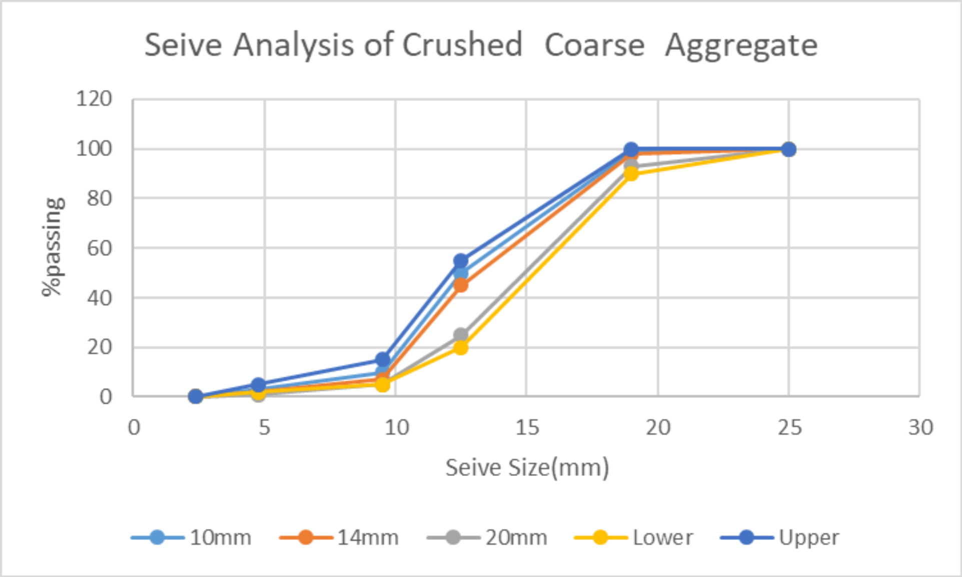

Figure 3: Coarse aggregate (sieve analysis)

In addition, WA and relative density of aggregates were measured based on ASTM C128-15 and C127-15 as shown in Table 2.

Table 2: WA and relative density of aggregates

Type of Aggregate	Bulk specific gravity		water absorption	Specific gravity
	Dry	SSD		
Fine aggregate	2.56	2.59	1.19	2.68
Coarse aggregate	2.41	2.55	1.69	2.56

3.2.4 Silica Fume

Silica fume was incorporated in SCC mixtures by 5, 7.5, and 10 % of cement weight. Various features of Silica Fume are presented in Table 3.

Table 3: Various features of Silica Fume (%)

Oxide compound	Silica fume
SiO_2	92.55
CaO	2.36
Al_2O_3	0.60
Fe_2O_3	0.79
MgO	0.15
$CaCO_3$	0.30
$MgCO_3$	-
SO_3	0.52
Free CaO	-
Specific gravity	2.22

3.2.5 Superplasticizer

Glenium 27 is a polycarboxylic ether-based superplasticizer which was added to concrete as a water-reducing agent. SP content was constant for all mixtures at 1% of cementitious material weight.

3.3 Mixing Proportions

Design proper type and amount of concrete material in mixing process is of great importance. Mix design complies with specifications of Building Research Establishment. Quantities of mixing materials are shown in Table 4.

Table 4: Mixing quantities of concrete

Type of Concrete	Cement (kg)	Water (kg)	FE (5mm)	CE (10 mm)	CE (14 mm)	CE (20 mm)	SF (kg)	SP (kg)	W/C Ratio
Control	450	225	767	328	375	235	-	4.5	0.5
SCC5 SF	427	213	767	328	375	235	22.5	4.27	0.5
SCC7.5 SF	416	208	767	328	375	235	33.7	4.16	0.5
SCC10 SF	405	202	767	328	375	235	45	4.05	0.5

FA: fine aggregate; CA: coarse aggregate

3.4 Experimental Procedure

In order to evaluate effect of SF inclusion as a substituent to cement, numerous tests regarding the SCC properties were performed and in following sections will be discussed.

3.4.1 Concrete Mixing Process

First step, dry coarse aggregate following by fine aggregate were introduced to mixer. After mixing for a minute little amount of water was added. Next step, silica fume, cement and water were gradually added and mixed for another 2 minutes. Then two-thirds of superplasticizer was incorporated in water and mixed for additional 2 minutes. Finally, remaining SP was added to mixture.

3.4.2 Tests of Fresh Properties

Workability of SCC with 0.5 W/C ration and inclusion of three different percentages (5, 7.5, and 10%) silica fume was determined by performing rheological examination.

3.4.2.1 Slump Flow

SCC slump experiment is conducted according to ASTM C1611/C1611M-21 standard. Same equipment and tools for slump of normal concrete are used. However, different method is required to measure slump of SCC. After filling the mold with concrete and let it flow under its own weight on base plate as is shown in the Figure 4, largest diameter of spread circular concrete should be measured. Another diameter perpendicular to first diameter should be recorded. Average of these two diameters represent the SCC's slump value.

Figure 4: SCC's slump

3.4.2.2 J-ring Flow

J-ring test was carried out in order to assess SCC passing ability with accordance to ASTM C1621/C1621M-17. Concrete mold is placed at the center J-ring apparatus and process of slump experiment of SCC is conducted by measuring two perpendicular diameters. Mean of these two diameters shows the value of J-ring slump flow.

3.4.2.3 L-box Experiment

Flow ability of SCC can be determined by L-box experiment. steep section of apparatus is loaded with concrete and after 1 minute, sliding gate will be opened to let concrete flow under its own weight to horizontal section as is shown in the Figure 5. When concrete stopped from flowing, height of concrete at vertical and horizontal sections (H2, H1) are measured. Reasonable range of (H2/H1) for SCC should be in the range of 0.8 to 1.

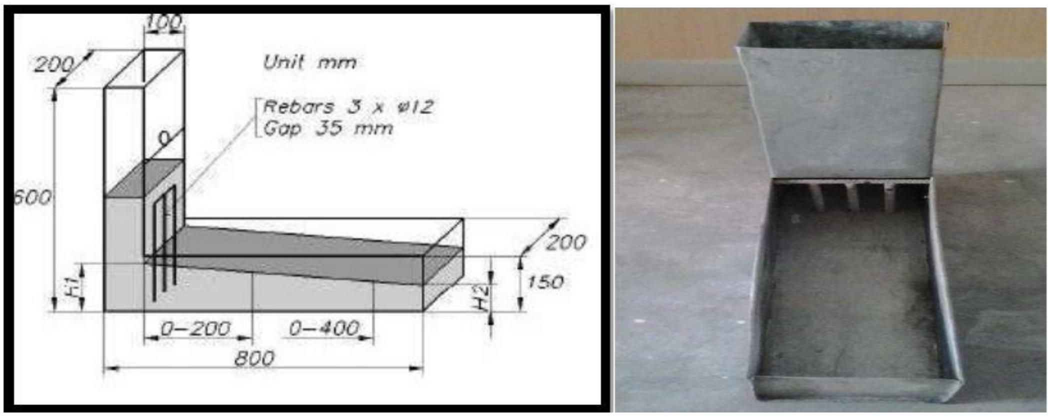

Figure 5: L-box apparatus

3.4.2.4 V-funnel Test

This test measures the capability of concrete to flow. Figure 6 shows the equipment which is loaded up with concrete and then required time to complete discharge of SCC by opening the below gate of V-funnel is recorded. Time values is recommended to be within the range of 6-12 seconds.

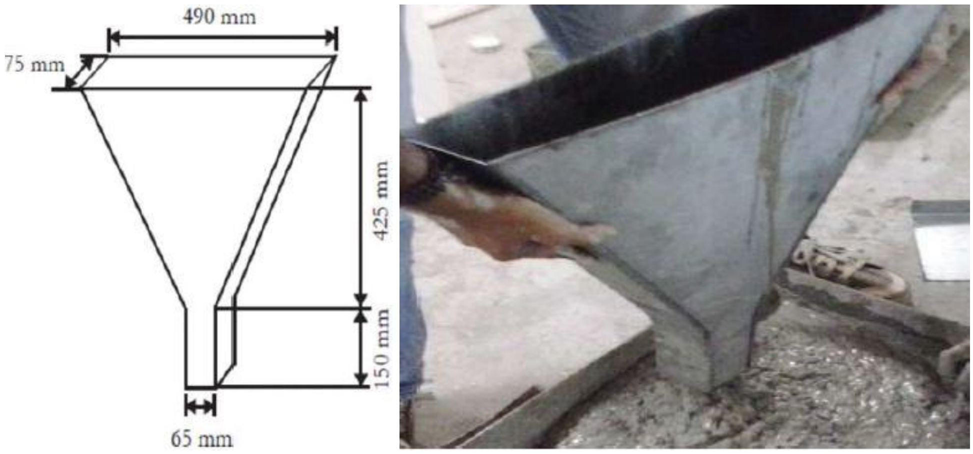

Figure 6: V-funnel equipment

3.4.3 Preparation and Curing of Concrete Samples

Totally 18 specimens were casted as follows; 12 cubic samples (150 mm × 150 mm × 150mm), 3 cylindrical specimens with dimensions of 100 mm × 200 mm, and 3 beams having 500 × 100 × 100 mm diameter. In order to prevent reaction between the casts and concrete, also easier demolding molds got cleaned and oiled. After performing the concrete fresh tests, molds were filled and kept in 20-degree Celsius room with humidity of 99% for 24 hours. Then specimens were demolded and placed in water tank with 20-degree Celsius temperature for 28-day curing.

3.5 Test of Hardened Properties

Compressive Strength measured at 3,7, and 28-day intervals. Splitting Tensile Strength, Flexural Strength and Schmidt hammer tests were performed at 28 days.

3.5.1 Compressive Strength

12 cubical specimens having size of 150 mm in each side was tested under compression load at 3,7, and 28 days to assess impact of 5, 7.5 and 10% SF inclusion on SCC strength. The loading machine measures the force required to deform or fracture the sample. Crushed sample with 7.5% silica fume is shown in Figure 7.

Figure 7: Crushed specimen containing 7.5% SF

3.5.2 Splitting Tensile

3 Specimens having cylindrical shapes and size of 100 × 200 mm were incorporated in experiments to investigate impact of 5, 7.5 and 10% SF inclusion on SCC tensile strength conforming to ASTM C496/C496M-17. Samples were crushed under axial loading in order to measure the values of splitting tensile strength as it can be seen in Figure 8.


Figure 8: Crushed cylinder sample under axially loading of machine

3.5.3 Flexural Strength

Three-point loading on beam specimens having size of 500 × 100 × 100 mm were carried out comply with ASTM C78/C78M-22 as is shown in the Figure 9.

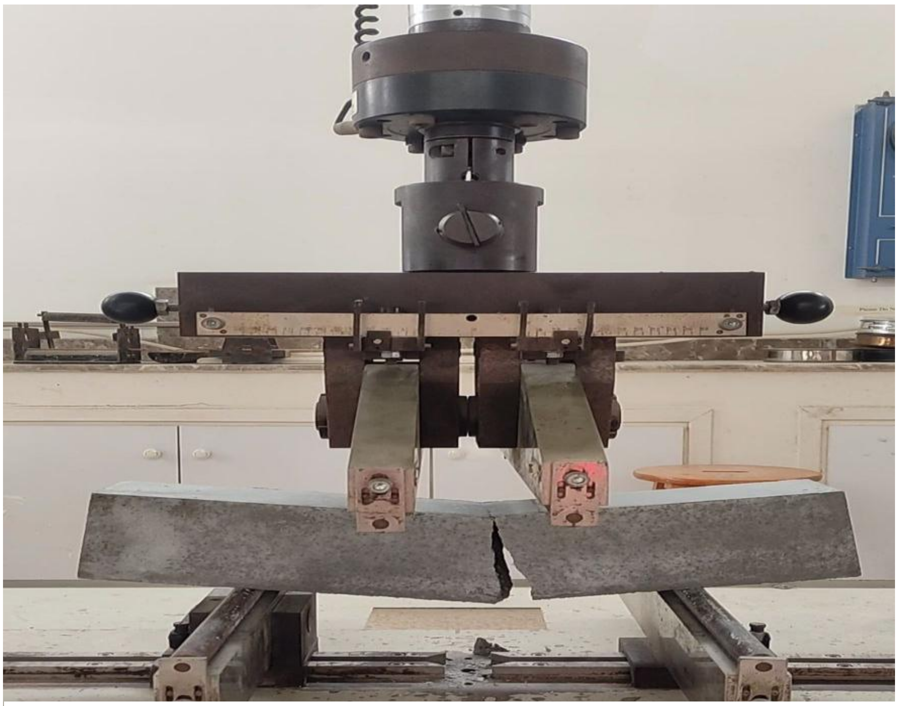
Figure 9: Crushed beam sample under three-point load

3.5.4 Ultrasonic Pulse Velocity

This is a nondestructive experiment to assess quality of concrete by recording speed of transmitted pulse waves through SCC. Low quality SCC with voids and cracks represents low values of velocity. Figure 10 shows that experiment was carried out on 150 mm cubic specimens at 28-day curing complying with ASTM C597-16.

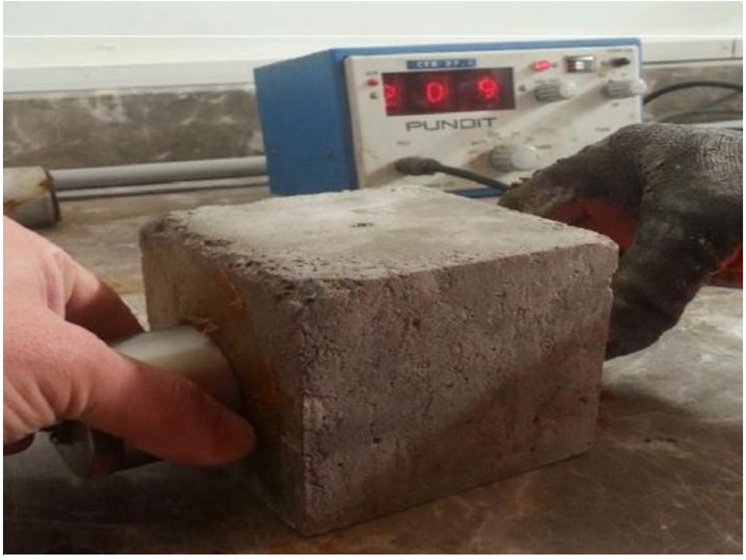

Figure 10: Ultrasonic pulse velocity test of sample

3.5.5 Schmidt Hammer

This experiment was performed conforming procedure of “ASTM C805/C805M-18”. 150 mm Cube specimens were placed under testing machine while maintain loading fixed in order to avoid movement of specimens. Then numbers of rebound developed by compacted hammer perpendicular to concrete were recorded. It was suggested that maximum difference between range of values is 12 units.

3.5.6 Water Absorption

Experiment was performed on 100 mm cubes conforming “ASTM C642-21” at 28 days. First, weight of 24hours oven dried specimens were measured. Second, weight of samples submerging in water for 2days were recorded. Then, cubes were boiled in water for 5hours and mass of surface drying cubes obtained. Finally, specimens after cooling down for 14hours were hanged in water and their mass was obtained. Absorptivity and porosity volume of SCC was achieved by this method.

Chapter 4

RESULTS AND DISCUSSIONS OF RESULTS

4.1 Introduction

Chapter 4 argues results obtained from experiments by representing graphs and tables regarding the tests. SF inclusion of 5,7.5, and 10% in SCC performance was evaluated by maintaining W/C at 0.5.

4.2 Influence of SF on workability

Table 5: Influence of SF on workability

Results of SCC workability					
Mixture	Slump flow test (mm)	J-Ring test(mm)	L-Box test (H1/H2)	V-Funnel test (sec)	Self-compacting concrete
Control	710	690	0.91	4.5	Satisfied
SCC5 SF	650	640	0.87	7.5	Satisfied
SCC7.5SF	600	580	0.85	10	Satisfied
SCC10SF	580	570	0.81	11	Satisfied

Impact of SF substitution on SCC workability are presented in Table 5. Data obtained from experiments exhibited SF inclusion up to 10 % led to acceptable values respecting the SCC workability. However, increasing the amount of SF subtituion up to 10% resulted in decline of slump to 130 mm in comparison to control mixture. It was noted difference between J-ring and slump values was less than 25 mm for all mixtures which is the indication of no probability of blocking phenomenon. 5 ,7.5 and

10% SF substituted SCC performed within the acceptable range of standards with respect of “V-funnel and L-box experiments”.

4.3 Influence of SF on Compressive Strength

Findings related to compression test of SCC having 5,7.5, and 10 % SF are illustrated in Table 6 and Figure 11. All the mixtures were categorized as high strength concrete having more than 40 MPa strength. SCC mixtures with silica fume show significantly higher strength at all ages compared to the control, indicating the effectiveness of silica fume in improving the concrete matrix. Silica fume enhances early strength due to its high pozzolanic activity, which accelerates the formation of calcium silicate hydrate (C-S-H). SCC7.5SF (41.23 MPa) achieved the highest early strength. SCC mixtures maintain their superiority, with SCC7.5SF again leading at 54.67 MPa. SCC10SF (49.27 MPa) lags slightly behind SCC7.5SF, possibly due to reduced workability or inefficient dispersion of silica fume at higher percentages at 7days. All SCC mixtures surpass the control by a large margin. SCC5SF, SCC7.5SF, and SCC10SF 28days strength was found to be 26,47 and 52% higher compared to control mixtures. It is noticeable that increasing the SF percentage from 5 to 10 led to increment of SCC strength at all ages. 27% enhancement in values were recorded while SF content increased from 5 to 10%. Although optimum volume of SF inclusion was found to be 7.5% regarding the short-time strength (3and 7 days). SCC10SF marginally outperforms SCC7.5SF, suggesting that the optimal silica fume content for compressive strength lies between 7.5% and 10%.

Table 6: Influence of SF on compressive strength

Compressive Strength (MPa)	Mixture			
	Control	SCC5SF	SCC7.5SF	SCC10SF
3days	23.2	31.5	39.9	35.6
	24.6	32.8	41.2	37.8
	26.8	33.3	42.6	39.3
7days	33.4	43.6	51.9	48.3
	35.5	46.2	53.1	49.2
	37.7	46.4	59	51.3
28days	40.1	53.8	60.8	61.7
	44.6	54.3	64.7	67.3
	45.3	55.5	66.1	68.3

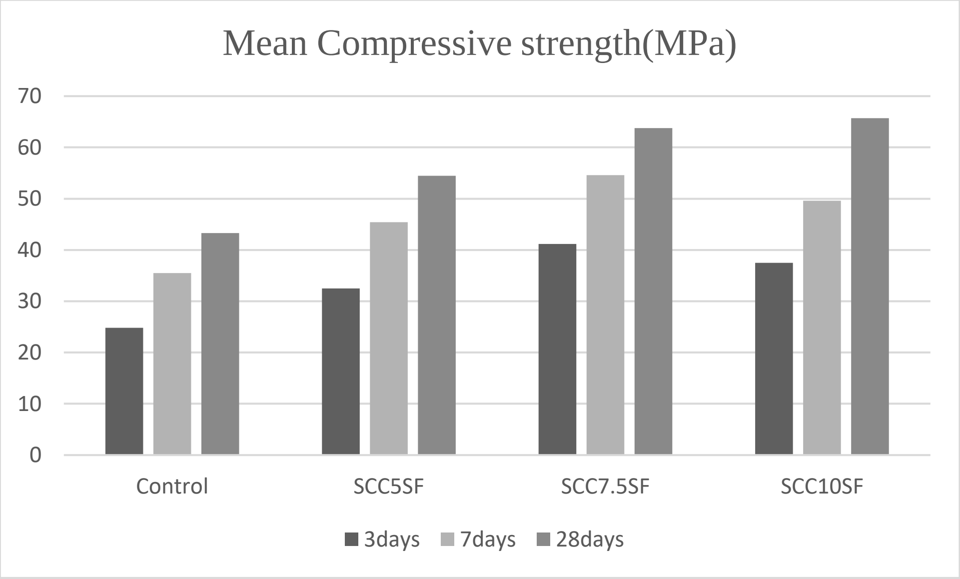

Figure 11: Compressive strength results

4.4 Regression Analysis of Compressive Strength

Application of regression analysis helps us to have better understanding of data trends, beside it will give us related equations to make future predictions. In order to assess how silica fume percentage relates to values of compressive strength, the variation regression types were calculated using models by specific relation factors R². Figures 12,13,14 and tables 7,8,9 exhibit relationship between percentage of silica fume and compressive strength of SCC for 3,7 and 28 days respectively, R² was measured in accordance with the regression type.

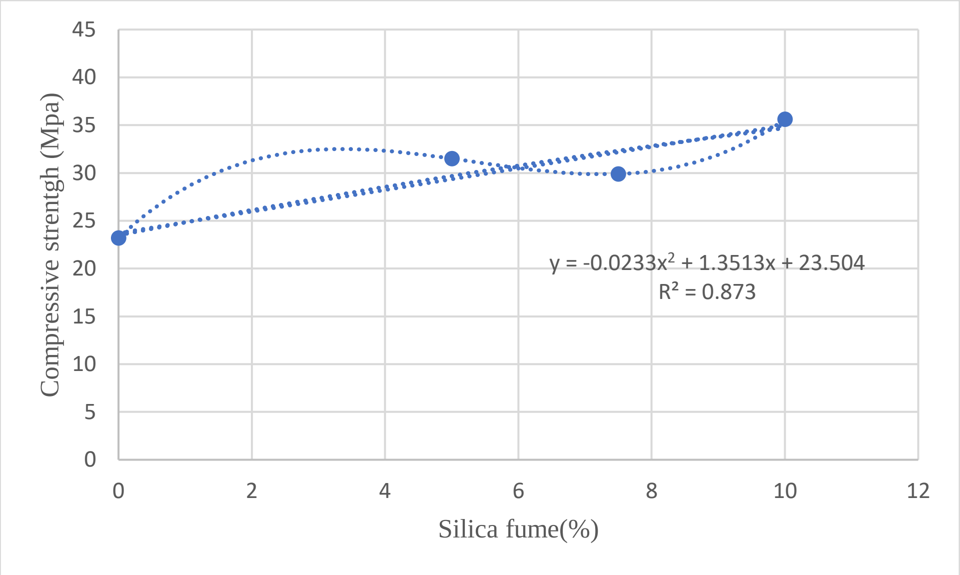

Figure 12: Correlation between Silica fume (%) and 3days compressive strength

Table 7: Correlation between Silica fume (%) and 3days compressive strength

Regression type	Equation	R²
Linear	$y = 1.1269x + 23.711$	0.8697
Exponential	$y = 23.787e^{0.0395x}$	0.861
Polynomial (2nd order)	$y = -0.0233x^2 + 1.3513x + 23.504$	0.873

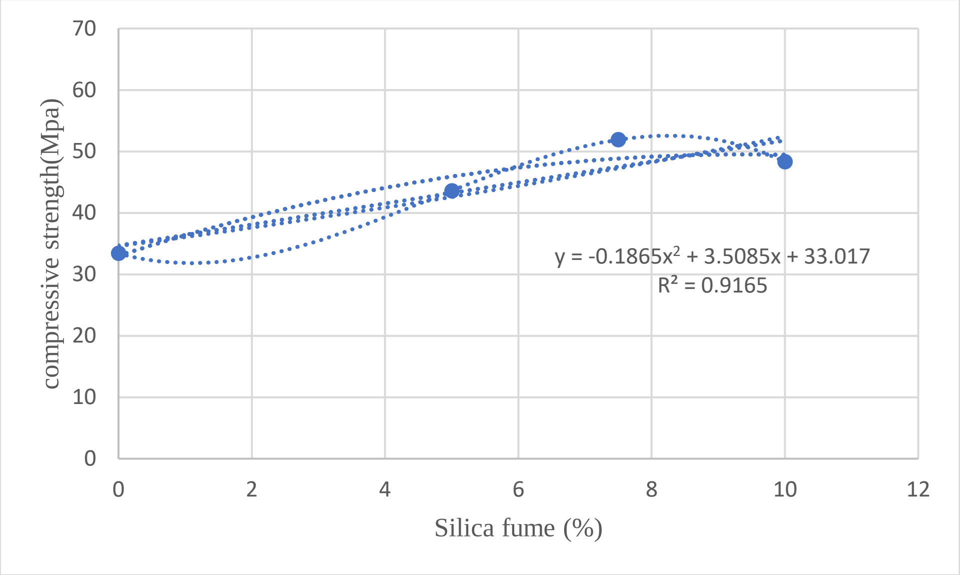

Figure 13: Correlation between Silica fume (%) and 7days compressive strength

Table 8: Correlation between Silica fume (%) and 7days compressive strength

Regression type	Equation	R²
Linear	$y = 1.7097x + 34.683$	0.828
Exponential	$y = 34.596e^{0.0416x}$	0.7903
Polynomial (2nd order)	$y = -0.1865x^2 + 3.5085x + 33.017$	0.9165

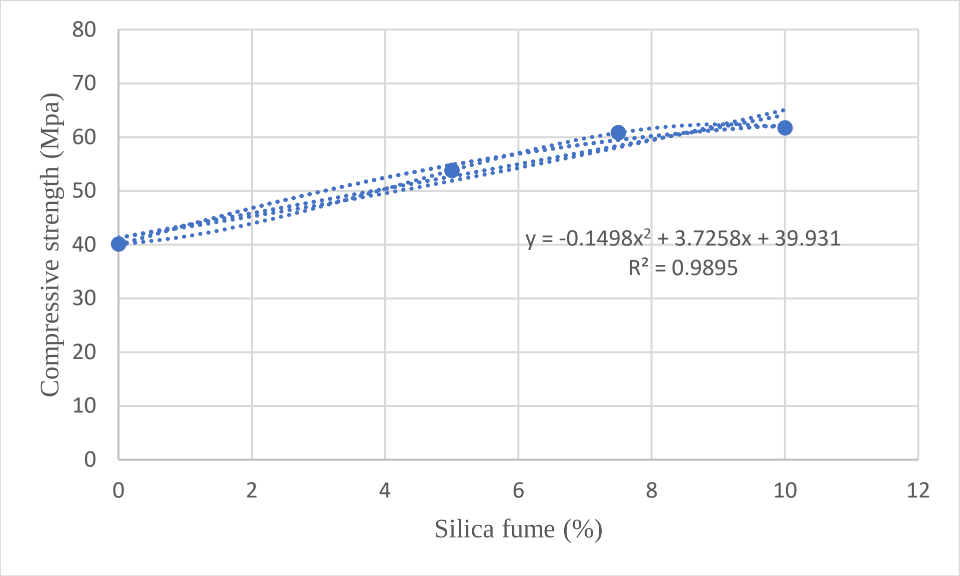

Figure 14: Correlation between Silica fume (%) and 28days compressive strength

Table 9: Correlation between Silica fume (%) and 28days compressive strength

Regression type	Equation	R^2
Linear	$y = 2.2811x + 41.269$	0.9526
Exponential	$y = 41.32e^{0.0454x}$	0.9221
Polynomial (2nd order)	$y = -0.1498x^2 + 3.7258x + 39.931$	0.9895

All the data showed the similar trend for compressive strength regardless of age of curing. Among all models, exponential was found to be the least favor to incorporate for forecasting with lowest values of R^2. Linear regression models performed well with high coefficient of determination and constant upward trend was observed. As far as, dataset is small or trying to predict future values with more precision, the 2nd order polynomial provides a good balance of fit and generalization.

4.5 Influence of SF on Splitting Tensile Strength

Results of experiment at 28 days are exhibited in Table 10 and Figure 15.

Table 10: Splitting Tensile values of subtituted SF-SCC

Mixture	SplittingTensile Strength (MPa)		
	28days		
Control	2.54	2.64	2.83
SCC5SF	3.10	3.17	3.43
SCC7.5SF	5.07	5.24	5.39
SCC10SF	3.89	4.98	5.25

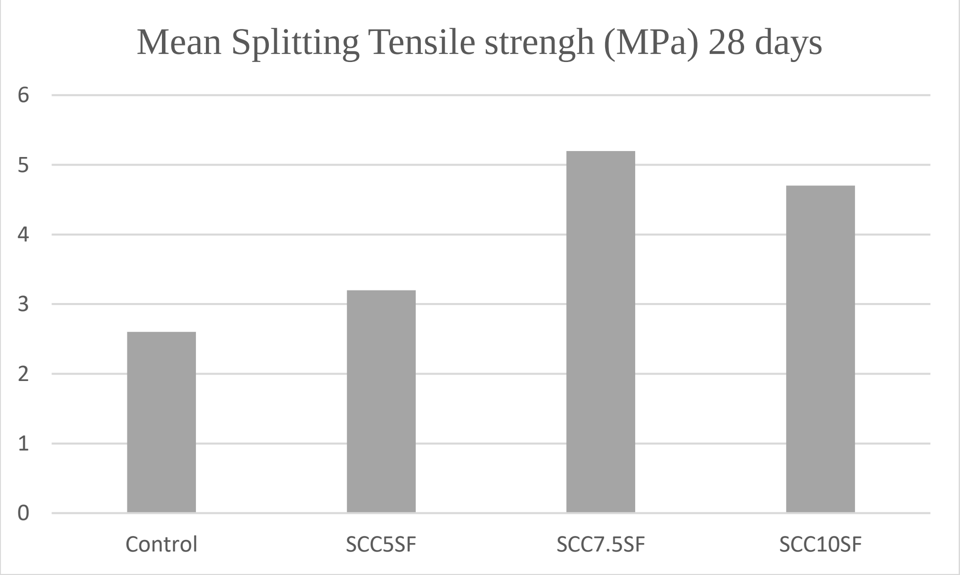

Figure 15: Splitting tensile strength results (28days)

The control mixture has the lowest splitting tensile strength at 2.67 MPa. Mixtures with silica fume demonstrate 21,96, and 76% higher strength for 5,7.5 and 10% Silica fume in comparison to control mixtures. The results confirm the beneficial effects of silica fume, attributed to its ability to refine the microstructure and enhance the bond strength in the concrete matrix. Data from Figure 13 indicated that increasing the SF percentage from 5 to 7.5 resulted in increment of "splitting tensile strength" about 62 %. Whereas, slight decrease (9%) in values were observed by increasing SF content to 10%. However, 10% inclusion of SF resulted in better performance of SCC in comparison with 5% SF SCC. SCC7.5SF achieved the highest splitting tensile strength (5.23 MPa), nearly double that of the control which indicate that introduction of 7.5% SF in SCC mixtures was found to be optimal amount in this experiment.

4.6 Influence of SF on Flexural Strength of SCC

Collected data from "Flexural strength experiment" at 28 days were depicted in Table 11 and Figure 16. The control mixture achieves the lowest flexural strength, averaging 5.59 MPa. Almost 10, 32, and 31% improvement in strength over control mixtures were obtained when 5,7.5, and 10% of Silica fume were added respectively. It can be seen clearly that raising content of SF replacement contributed to progress in strength gaining of SCC. Despite the fact that 7.5% SF inclusion led to increment of strength to peak level. At SF substitution level of 10% strength was found to be almost equal to highest values. SCC7.5SF provides the best overall performance, achieving the highest flexural strength (7.37 MPa) and a 31.8% improvement over the control. It represents the optimal silica fume content for enhancing flexural properties. While SCC10SF also shows significant improvement, it does not outperform SCC7.5SF, indicating diminishing benefits at higher silica fume content. SCC5SF offers a smaller improvement but may still be a viable option for less demanding applications due to its lower cost and adequate performance.

Table 11: Influence of SF on Flexural Strength

Mixture	Flexural Strength (MPa)		
	28days		
Control	5.12	5.70	5.95
SCC5SF	5.22	6.40	6.73
SCC7.5SF	6.90	7.57	7.63
SCC10SF	7.16	7.39	7.22

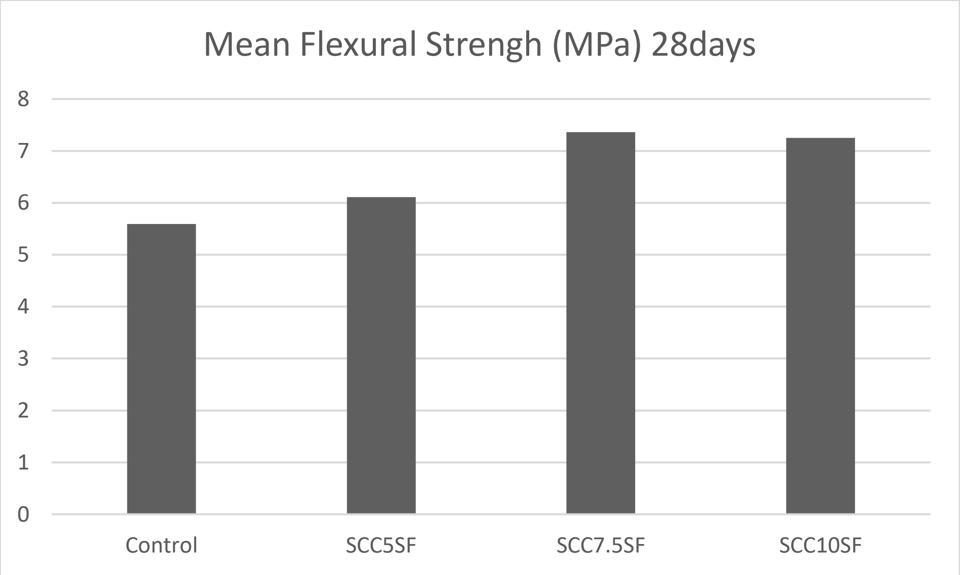

Figure 16: Flexural strength test results

4.7 Influence of SF on Ultrasonic Pulse Velocity

Velocity of ultrasound wave through specimens was recorded and results are demonstrated in Table 12. All SCC mixtures having SF satisfied standard limit of standard and considered as SCC with reasonably good quality. All SCC mixtures exhibit slightly higher average pulse velocity, indicating better quality and density. SCC7.5SF achieved the highest average pulse velocity (4.61 km/s), demonstrating the optimal improvement in concrete quality and uniformity. SCC10SF (4.54 km/s) shows slightly lower performance compared to SCC7.5SF. This could be due to Potential microcracking or reduced workability at higher silica fume content, besides excess silica fume leading to segregation or increased voids during mixing. Increment in percentage of SF replacement decreased the velocity slightly. This could be attributed to denser microscopic structure of SCC at inter-face zone due to filling capability of SF fine particles. Overall, use of silica fume in SCC improves pulse velocity, confirming its role in enhancing the density and microstructural quality of concrete. Higher pulse velocity in SCC indicates a denser, more compact, and uniform material, suitable for structural applications where durability and reduced permeability are critical.

Table 12: Impact of SF inclusion on SCC's velocity of ultrasound wave

Type of Specimens	Time(μs)	Pulse velocity (km/sec)
Control	30.10	4.44
	30.40	4.48
	30.70	4.53
SCC5SF	31.20	4.80
	32.50	4.60
	35.60	4.20
SCC7.5SF	32.10	4.67
	32.30	4.64
	33.10	4.53
SCC10SF	32	4.69
	33.50	4.48
	33.70	4.45

4.8 Schmidt Hammer

Hammer experiment was performed on SCC having diverse percentage (5, 7.5, and 10) SF. Number of rebound were recorded as shown in Table 13. SCC7.5SF shows the strongest correlation between rebound number (34.5) and compressive strength (66.1 MPa), suggesting that rebound number accurately reflects its compressive strength. SCC10SF shows a high compressive strength (68.3 MPa) but a relatively low rebound number (31.3). This may indicate inconsistencies in the surface properties or a reduced correlation between rebound number and compressive strength at higher silica fume contents. SCC5SF and Control samples Rebound numbers and compressive strengths show a consistent relationship, with lower values compared to SCC7.5SF and SCC10SF. SCC7.5SF achieved the best balance between surface hardness (rebound number) and compressive strength, making it ideal for applications requiring both high strength and durability. However, SCC10SF has the highest compressive strength, but the variability in rebound number suggests potential microstructural inconsistencies at higher silica fume content. The control mixture exhibits the lowest values in all metrics, highlighting the benefits of adding silica fume to SCC for enhanced performance. Specification of standard test was satisfied because; difference between the readings were found to be less than 12. Estimated compressive strength obtained from the related graph of Schmidt hammer test showed significant difference compared to real values. The reason could be that SCC tends to retain moisture differently due to its dense microstructure.

Wet surfaces reduce rebound numbers, possibly causing underestimation of compressive strength. Furthermore, SCC has different paste to aggregate distribution, lower bleeding and higher fines content compared to normal concrete. This could change how rebound numbers correlate with true strength. Therefore, it can be concluded Schmidt hammer test measures the hardness of concrete and not strength of the full cross-section.

Table 13: Schmidt hammer experiment of SF-SCC

Mixture	SCC5SF	SCC7.5SF	SCC10SF	Control
Rebound Number	32	34	31	33
	35	35	30	30
	34	34	31	29
	34	34	33	31
	32	36	30	32
	32	35	32	31
	30	33	31	30
	29	35	33	33
	29	33	29	29
	30	36	33	33
Compressive Strength	55.5	66.1	68.3	41.2
Estimated Compressive Strength	25	27.3	28.1	24.2

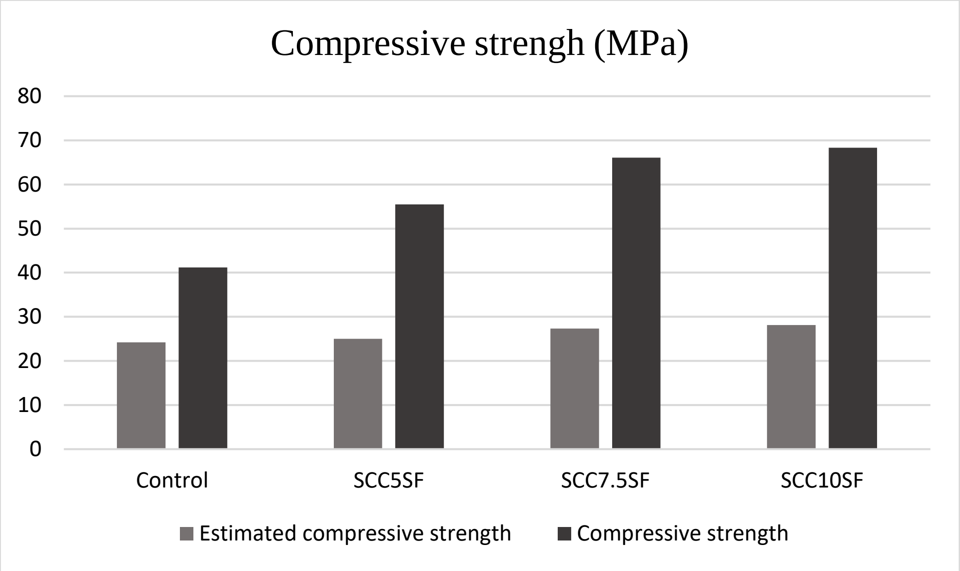

Figure 17: Comparison between Schmidt hammer strength and actual compressive strength

Data from Figure 17 showed huge difference between strength values from Schmidt hammer test and actual compressive strength. This discrepancy shows the limitations of the Schmidt hammer, variations in SCC properties, and the influence of surface conditions. This test measures the rebound of a spring-loaded mass after impact with the concrete surface. This rebound value is then correlated with compressive strength through empirical relationships, which may not be perfectly accurate for all concrete types, especially SCC. Moreover, the Schmidt hammer is highly sensitive to surface conditions, such as moisture, carbonation, and surface texture. These factors can significantly affect the rebound value, leading to inaccurate strength estimations. In addition, self-compacting concrete has unique characteristics like high flowability and reduced segregation, which can influence the rebound value compared to traditional concrete.

4.9 Water Absorption

Absorption and volume of voids are represented by percentage in Table 14. SCC5SF shows the highest ability to absorb water when submerged, possibly indicating a higher porosity or a different mix ratio that leads to more water retention. SCC7.5SF and SCC10SF show lower submerged absorption, with SCC7.5SF having the lowest. This suggests that increasing the amount of silica fume may reduce the absorption. Silica fume is known to densify the concrete matrix, reducing voids and, thus, absorption. Boiling increases the absorption rate because it removes water from capillary pores and allows for further absorption once submerged. SCC5SF again has the highest absorption, suggesting that the mixture is more porous or has larger capillary voids than the others. SCC7.5SF and SCC10SF both have fewer permeable voids, suggesting that higher silica fume content helps to reduce the porosity of the mixture. The reduced permeable voids are likely contributing to the lower absorption observed in these mixtures. Experiment finding suggested that decline in capacity of absorption and voids of SCC can be achieved whilst SF substitution level was increased. Raising percentage of SF inclusion from 5 to 7.5 and 10 in SCC led to decline of absorptivity by 35 and 28% respectively. In addition, volume of permeable voids decreased 30 and

27%, while SF content increased from 5 to 7.5 and 10% respectively. This behavior explains that inclusion of SF resulted in less permeable and consequently much durable SCC. Reasons behind this behavior could be firstly, Silica fume due to its filler effect and fine particles fills the voids between cement particles and aggregates. This reduces the overall pore structure in the hardened concrete, leading to a denser microstructure. Secondly, Silica fume reacts with calcium hydroxide in a pozzolanic reaction. This reaction produces additional calcium silicate hydrate (C-S-H) gel, which increases the density of the concrete, reducing the amounts of interconnected pores and capillaries. As a result, the overall porosity decreases, and the size of any remaining pores is smaller, which reduces the ability of water and chemicals to penetrate the concrete.

Table 14: Water absorption and voids volume

Mixture	submerged absorption (%)	submerged and boiled absorption (%)	permeable voids (%)
SCC5SF	4.70	4.90	10.70
SCC7.5SF	3.06	3.20	7.40
SCC10SF	3.30	3.50	7.80

4.9.1 Relationship between Ultrasonic Pulse Velocity and Permeable Voids

Table 15: Pulse velocity and permeable voids

Mixture	Pulse velocity (km/s)	Permeable voids (%)
SCC5SF	4.53	10.70
SCC7.5SF	4.61	7.40
SCC10SF	4.54	7.80

In SCC, the relationship between ultrasonic pulse velocity and permeable voids is generally inverse. Higher values of velocity for concrete indicate denser and more cohesive microstructure with fewer pores and microcracks. Table 15 presents pulse velocity values ranges from 4.5 to 5.5 km/s which is the indication of good quality SCC often containing 7 to 10% permeable voids. Within samples, inclusion of 7.5% of silica fume led to lowest permeable voids (%) at 7.4. Although, increasing silica fume from 7.5 to 10% increased the voids slightly but it was found to be 27% less permeable voids compared to samples containing 5% silica fume. This behavior could be attributed to poor dispersion of particles in concrete and formation of voids and microcracks in concrete matrix after inclusion of 10% silica fume. Another reason could be different temperature of these samples during the curing time in comparison to other samples. Based on the small data set of this study below relationship between ultrasonic pulse velocity and permeable voids can be equated.

$$\text{Permeable void (\%)} = 137.03 - 28.16 \times \text{Pulse velocity (km/s)}$$

Chapter 5

CONCLUSIONS

5.1 Conclusions

Cement was substituted with SF partially at diverse percentages of (5, 7.5 and 10%) while keeping the ratio of water to cement fixed at 0.5. According to obtained values from experiments of this study following conclusions can be drawn.

All the SCC exhibited reasonable performance except SCC10SF respecting the plastic characteristics. SF inclusion up to 7.5 % led to acceptable values respecting the SCC workability. However, increasing the amount of SF subtituion up to resulted in decline of slump to 110 mm.

Increment of compression test values were recorded while SF content increased from 5 to 10%. Although optimum volume of SF inclusion was found to be 7.5% regarding the strength for short period of curing.

Splitting tensile strength values were increased up to 62 % by raising the percentage of SF inclusion from 5 to 7.5. Whereas, slight decrease (9%) in values were observed by increasing SF content from 7.5 to 10%.

Despite the fact that 7.5% SF inclusion led to increment of strength to peak level. At SF substitution level of 10% strength was found to be almost equal to highest values with respect to “flexural strength”.

Findings of Ultrasound wave velocity and Schmidt hammer experiments indicated SF inclusion enhanced the SCC quality and microscopic structure.

Decline in capacity of absorption and voids of SCC can be achieved whilst SF substitution level was increased. Volume of permeable voids decreased 30 and 27%, while SF content increased from 5 to 7.5 and 10% respectively.

5.2 Further Research Opportunity

Future case studies can evaluate the fresh and hardened behavior of SCC containing SF along with other SCMs in binary and ternary mixtures. Moreover, assessment of SCC with inclusion of diverse type and dosage of SP along with SF could provide additional benefits to obtain appropriate mixing design for SCC.

REFERENCES

ACI Committee 237 (Ed.). (2007). Self-consolidating concrete. American Concrete Institute.

Alrawashdeh, A., & Eren, O. (2022). Mechanical and physical characterisation of steel fibre reinforced self-compacting concrete: Different aspect ratios and volume fractions of fibres. Results in Engineering, 13, 100335.

Benaicha, M., Belcaid, A., Alaoui, A. H., Jalbaud, O., & Burtschell, Y. (2019). Effects of limestone filler and silica fume on rheology and strength of self-compacting concrete. Structural Concrete, 20(5), 1702–1709.

Benaicha, M., Roguiez, X., Jalbaud, O., Burtschell, Y., & Alaoui, A. H. (2015). Influence of silica fume and viscosity modifying agent on the mechanical and rheological behavior of self-compacting concrete. Construction and Building Materials, 84, 103–110.

Bernal, J., Reyes, E., Massana, J., León, N., & Sánchez, E. (2018). Fresh and mechanical behavior of a self-compacting concrete with additions of nano-silica, silica fume and ternary mixtures. Construction and Building Materials, 160, 196–210.

Çelik, Z., Bingöl, A. F., & Ağsu, A. S. (2022). Fresh, mechanical, sorptivity and rapid chloride permeability properties of self-compacting concrete with silica fume and fly ash. Iranian Journal of Science and Technology, Transactions of Civil Engineering, 46(2), 789–799.

Cheah, C. B., Chow, W. K., Oo, C. W., & Leow, K. H. (2020). The influence of type and combination of polycarboxylate ether superplasticizer on the mechanical properties and microstructure of slag-silica fume ternary blended self-consolidating concrete. Journal of Building Engineering, 31.

Dehwah, H. A. F. (2012). Mechanical properties of self-compacting concrete incorporating quarry dust powder, silica fume or fly ash. Construction and Building Materials, 26(1), 547–551.

EFNARC. (2002). Specification and Guidelines for Self-Compacting Concrete.

Esfandiari, J., & Loghmani, P. (2019). Effect of perlite powder and silica fume on the compressive strength and microstructural characterization of self-compacting concrete with lime-cement binder. Measurement, 147, 106846.

Etli, S. (2023). Evaluation of the effect of silica fume on the fresh, mechanical and durability properties of self-compacting concrete produced by using waste rubber as fine aggregate. Journal of Cleaner Production, 384, 135590.

Frhaan, W. K., Bakar, H. B., Hilal, N., & Al-Hadithi, A. I. (2020a). Effect of silica fume and super-plasticizer on mechanical properties of self-compacting concrete: A Review. IOP Conference Series: Materials Science and Engineering, 978, 012052.

Gesoğlu, M., & Özbay, E. (2007). Effects of mineral admixtures on fresh and hardened properties of self-compacting concretes: Binary, ternary and quaternary systems. Materials and Structures, 40(9), 923–937.

Jalal, M., Pouladkhan, A. R., Ramezanianpour, A. A., & Norouzi, H. (2012). Effects of silica nanopowder and silica fume on rheology and strength of high strength self-compacting concrete. Journal of American Science, 8(4), 270–277.

Kennouche.S. (2013). Formulation and characterization of self-compacting concrete with silica fume. Journal of Engineering and Technology Research, 5(5), 160–169.

Khayat, K. H., & De Schutter, G. (Eds.). (2014). Mechanical properties of self-compacting concrete: State-of-the-art report of the rilem technical committee 228-mps on mechanical properties of self-compacting concrete (Vol. 14). Springer International Publishing.

Lisantono, A., & Pratama, Y. P. B. (2020). Effect of silica fume on the compressive strength and modulus elasticity of self-compacting high strength concrete. IOP Conference Series: Earth and Environmental Science, 426(1), 012057.

Lu, C., Yang, H., & Mei, G. (2015). Relationship between slump flow and rheological properties of self-compacting concrete with silica fume and its permeability. Construction and Building Materials, 75, 157–162.

Mahalakshmi, S. H. V., & Khed, V. C. (2020). Experimental study on M-sand in self-compacting concrete with and without silica fume. Materials Today: Proceedings, 27, 1061–1065.

Mastali, M., & Dalvand, A. (2016). Use of silica fume and recycled steel fibers in self-compacting concrete (SCC). Construction and Building Materials, 125, 196–209.

Mazloom, M., Soltani, A., Karamloo, M., Hassanloo, A., & Ranjbar, A. (2018). Effects of silica fume, superplasticizer dosage and type of superplasticizer on the properties of normal and self-compacting concrete. Advances in Materials Research, 7(1), 407–434.

Mohammadi, Y., Mousavi, S., Rostami, F., & Danesh, A. (2015). The effect of silica fume on the properties of self-compacted lightweight concrete. Current World Environment, 10(Special-Issue1), 381–388.

Nikbin, I. M., Beygi, M. H. A., Kazemi, M. T., Vaseghi Amiri, J., Rabbanifar, S., Rahmani, E., & Rahimi, S. (2014). A comprehensive investigation into the effect of water to cement ratio and powder content on mechanical properties of self-compacting concrete. Construction and Building Materials, 57, 69–80.

Ofuyatan, O. M., Adeniyi, A. G., & Ighalo, J. O. (2021). Evaluation of fresh and hardened properties of blended silica fume self-compacting concrete (SCC). Research on Engineering Structures and Materials.

Pang, L., Liu, Z., Wang, D., & An, M. (2022). Review on the application of supplementary cementitious materials in self-compacting concrete. Crystals, 12(2), 180.

Raymond A, Y., Januarti Jaya, E., & Triwulan. (2017). Optimizing high performance self-compacting concrete. MATEC Web of Conferences, 97, 01027.

RILEM Technical Committe. (2006). Final report of RILEM TC 188-CSC ‘Casting of self-compacting concrete.’ Materials and Structures, 39(10), 937–954.

Sasanipour, H., & Aslani, F. (2019). Effect of specimen shape, silica fume, and curing age on durability properties of self-compacting concrete incorporating coarse recycled concrete aggregates. Construction and Building Materials, 228, 117054.

Sasanipour, H., Aslani, F., & Taherinezhad, J. (2019). Effect of silica fume on durability of self-compacting concrete made with waste recycled concrete aggregates. Construction and Building Materials, 227, 116598.

Sharbatdar, M. K., Abbasi, M., & Fakharian, P. (2020). Improving the Properties of Self-compacted Concrete with Using Combined Silica Fume and Metakaolin. Periodica Polytechnica Civil Engineering.

Smirnov, A. O., Dobshits, L. M., & Anisimov, S. N. (2020). Effect of superplasticizer and silica fume on the properties of self-compacting mortars. IOP Conference Series: Materials Science and Engineering, 896(1), 012095.

Turk, K., Karatas, M., & Gonen, T. (2013). Effect of fly ash and silica fume on compressive strength, sorptivity and carbonation of scc. KSCE Journal of Civil Engineering, 17(1), 202–209.

Vivek, S. S. (2021). Fresh and hardened state properties of ternary blend self-compacting concrete using silica fume and ground granulated blast furnace slag. Revista Română de Materiale / Romanian Journal of Materials, 51(3), 414–422.

Yazıcı, H. (2008). The effect of silica fume and high-volume Class C fly ash on mechanical properties, chloride penetration and freeze–thaw resistance of self-compacting concrete. Construction and Building Materials, 22(4), 456–462.