Engineering Properties of Steel Fiber Reinforced Self-Compacting Concrete (SFR-SCC)

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ABSTRACT

Self-compacting concrete (SCC) is a durable, highly flowable concrete with no tendency for segregation. It can easily fill complex formwork and passing through enclosing dense bars, and it consolidates without any need of vibration. SCC has the same brittle behavior as plain concrete, but this shortcoming can be eliminated by the inclusion of reinforcing fibers which carry tension forces and improve mechanical properties.

This study investigates the effect of using steel fiber to reinforce self-compacting concrete and evaluate the improvement on physical and mechanical properties of the SCC matrix. For this purpose, six mixes of steel fiber reinforced self-compacting concrete (SFRSCC) were prepared with two different steel fiber aspect ratios of 60 and 80 l/d at three volume fractions (V_f) of 0.35%, 0.45%, and 0.55%, in addition to a control mix. All samples were casted with constant w/b ratio 0.34 and 2% silica fume of cement content as additive. The experimental results indicated that adding hooked end steel fiber slightly affected the compressive strength, ultrasonic pulse velocity, and permeability. On the other hand, adding the fibers increased the flexural strength, toughness, split tensile strength, and impact resistance of SCC depending on aspect ratio (l/d) and volume fraction (V_f).

Keywords: Self-Compacting Concrete, Steel Fiber, Silica Fume, Mechanical Properties, Workability, Flexural Strength, Toughness, Impact Resistance, Durability.

ÖZ

Kendiliğinden yerleşen beton (KYB), ayrışma eğilimi olmayan, dayanıklı, oldukça akışkan bir betondur. Karmaşık kalıpları kolayca doldurabilir ve ağır çubukları sarabilir ve herhangi bir titreşim gerektirmeden konsolide olur. KYB, düz beton ile aynı gevrek davranışa sahiptir, ancak bu eksiklik, gerilme kuvvetleri taşıyan ve mekanik özellikleri iyileştiren takviye elyafın dahil edilmesiyle ortadan kaldırılabilir.

Bu çalışma, kendiliğinden yerleşen betonu güçlendirmek için kanca uçlu çelik elyaf kullanımının etkisini araştırmakta ve KYB matrisinin fiziksel ve mekanik özellikleri üzerindeki gelişmeyi değerlendirmektedir. Bu amaçla,%0,35,%0,45 ve %0,55'lik üç hacim oranında, 60 ve 80 olarak iki farklı çelik elyaf en boy oranıyla kontrol karışımına ek olarak altı çelik elyaf takviyeli kendiliğinden yerleşen beton karışımı hazırlanmıştır. Tüm numuneler sabit su/çimento oranı ve %2 silis dumanı ile dökülmüştür. Deneysel sonuçlar, kanca uçlu çelik elyafın eklenmesinin basınç dayanımını, ultrasonik ses hızını ve geçirgenliği az miktarda etkilediğini göstermiştir. Öte yandan, kanca uçlu Çelik elyafın betona eklenmesi, en boy oranına ve hacim fraksiyonuna bağlı olarak KYB'nin bükülme mukavemetini, tokluğunu, basmada yarma mukavemetini ve darbe direncini artırmıştır.

Anahtar Kelimeler: Kendiliğinden Yerleşen Beton, Çelik Elyaf, Silis Dumanı, Mekanik Özellikler, İşlenebilirlik, Eğilme Dayanımı, Tokluk, Darbe Dayanımı, Dayanıklılık.

DEDICATION

To My Family

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LIST OF SYMBOLS AND ABBREVIATIONS

Agg	Aggregate
EFNARC	The European Federation of Specialist Construction Chemicals and Concrete Systems
HPC	High Performance Concrete
IR	Impact Resistance
l/d	Aspect Ratio
SCC	Self-Compacting Concrete
SF	Silica Fume
SFR-SCC	Steel Fiber Reinforced Self-Compacting Concrete
StF	Steel Fiber
UPV	Ultrasonic Pulse Velocity
V_f	Volume fraction
W/b	Water/Binder ratio
σ_c	Compressive Strength
σ_f	Flexural strength
σ_s	Splitting Tensile strength

Chapter 1

INTRODUCTION

1.1 General

There is no doubt that concrete has been one of the most widely used materials in structural building in recent years. With the improvement of the concrete design technology process, researchers have managed to produce a type of concrete called self-compacting concrete (SCC), which is easily placed in the narrow formwork and envelope heavy reinforced bars under its own weight (Loukili et al., 2013). This kind of concrete was produced in Japan by a group of researchers in 1986 as a good solution to get durable concrete with high performance. SCC requires fewer skilled workers to place it, and it causes less noise compared to vibrated concrete. In addition, it has high deformability due to low flow resistance with optimum viscosity, which makes it easy to place and compact without any need of vibration (Okamura et al., 2003).

Due to the brittle nature of plain concrete under tensile loading, and in order to prevent sudden failure, researchers are working to enhance the mechanical properties of normal concrete, including indirect tensile and flexural strengths, through adding randomly discrete fibers to help control crack propagation. Since SCC is weak under tensile forces as well, using steel fibers can also improve the ductility and performance under dynamic loading. On the other hand, the amount of fiber has to be limited depending on its type, shape, and length, and also depending on the composition of the SCC. The optimum amount of fiber should be determined in such a way as to cause the minimum decrease in fresh properties and the least effect on flow and passing ability, and at the same time, to achieve the maximum improvement on the different concrete properties (Luo et al., 2000; Deeb et al., 2012; Kulasegaram et al., 2011).

New generation superplasticizers are used as high range water reducers and viscosity modifiers in the production of SCC, whereas supplementary cementitious materials or fillers, such as limestone, silica fume, fly ash and natural pozzolans, are used to enhance the viscosity and the workability of fresh concrete (Gencel et al., 2011). High content of mineral admixtures added in powder form is an essential aspect in the proper design of self-compacting concrete, and both natural and manufactured minerals are employed including fly ash, silica fume and blast furnace slag. The use of these admixtures has the environmental advantage of reducing CO_2 emission by allowing lower amounts of cement to be used in SCC (Yazıcı, 2008).

1.2 Significance of the Study

It is important to optimize the methodology of adding steel fiber to SCC with minimal effect on fresh concrete properties. Steel fiber reinforced self-compacting concrete (SFR-SCC) has the potential to improve construction industries and facilitate concrete casting. First, it improves the ductility of large-dimension slabs and prevents the formation of cracks, which enhances the quality of the concrete. Second, it allows higher design flexibility since it achieves compaction in structure members where vibrating compaction is difficult to implement, and it minimizes the use of main steel bars by adding steel fibers to the mixture. Third, it eliminates the noise caused by vibration, which is especially needed in urban areas and in concrete production plants (precast concrete). Forth, it reduces the total cost of large-scale construction projects, due to using self-compacting concrete which saves the cost of vibrating compaction. Furthermore, adding steel fibers to SCC improves mechanical properties (σ_s, σ_f, modulus of elasticity, and micro-macro cracking behaviors). The significance of this research is the elucidation of the effect of adding hooked end StF at two different l/d and three various volume fractions, and determining the maximum improvement that can be achieved on the fresh and hardened properties of SCC.

1.3 Objective of the Study

The aims of this research study are develop the optimized design of steel fiber reinforced self-compacting concrete based on fresh performance and hardened properties, evaluate and compare engineering properties of SFR-SCC with two different aspect ratios of steel fiber added to plain SCC with a constant water to binder ratio. In addition, silica fume is added at 2% of cement content as an additive, limestone powder as a filler, and superplasticizer (Sika ViscoCrete Hi-Tech 51) as chemical admixture to achieve desirable fresh properties. For this purpose, seven mixes are prepared by adding steel fibers of 30 and 50 mm lengths with aspect ratios of 60 and 80 respectively, at volume fractions of 0.35%, 0.45%, and 0.55% for each length, and one control mix without steel fiber.

In order to estimate the influence of steel fiber inclusion on the characteristics of SCC, the following experiments are carried out on different prepared samples:

- Fresh tests.
- Mechanical tests (compressive, split, and flexural strengths).
- Obtaining the load-deflection curve.

- Impact resistance test.
- Non-destructive tests: Schmidt hammer test and Ultrasonic pulse velocity test.
- Permeability test (depth of penetration of water under pressure).

The factors that affect the physical and mechanical properties are analysed. After evaluating the results, the study allows the formulation of a recommendation with respect to the optimum amount of steel fiber alongside other added materials that achieve a highly flowable fiber-reinforced SCC with high performance.

1.4 Structure Of the Study

This study is organized into the following chapters: chapter one introduces the main subject of this research, whereas chapter two offers a literature review of the properties of the materials used in this study and their effect on concrete behavior. Chapter three explains the experimental work, mix design, test methods, and selection materials. Result analysis and critical discussion of the data is presented in chapter four. Finally, conclusions and recommendations are given in chapter five.

Chapter 2

LITERATURE REVIEW

2.1 Self-Compacting Concrete

Self-compacting is one of the most advanced technologies that have been introduced in concrete industry over the years. It is classified as a high performance concrete with perfect deformability and high resistance to segregation. It can fill corners and narrow places and can pass around the bars under the action of its own weight without requiring compaction, and with a minimum number of laborers to cast the concrete. This kind of concrete acts like a liquid which enables it to fill the formwork under the action of its own weight. At the same time, the mixture should be stable to prevent the segregation of solid particles. Mix proportions of SCC usually encompass the following ranges: low water cement ratio around 0.4, high content of cementitious material (powder content) at about 500-650 kg/m^3, low coarse aggregate volume not exceeding 32% of the total volume, in addition to some admixtures to help achieve these requirements (Tripathi et al., 2020; Shahidan et al., 2017; Okamura et al., 1995; Spangenberg et al., 2010).

2.2 Mineral Admixture

An admixture is any material added to concrete other than the basic materials like water or aggregate to improve fresh or hardened properties of concrete. Mineral admixture or pozzolanic material is defined as siliceous or silico-aluminous material and can be of natural or artificial origin. Some examples of these admixtures include fly ash, SF, metakaolin, blast furnace slag and rice husk. These materials react with calcium hydroxide $Ca(OH)_2$ to produce compounds that have cementitious properties. Some authors divide artificial pozzolans into two main groups based on their behavior in the mix: chemically active (Silica fume and metakaolin), and micro-filler (other materials) mineral admixtures. The first group is more reactive than the second and has a higher water demand to maintain workability. To solve this, plasticizer or superplasticizer is added to the concrete mixture. The second group has low heat of hydration and requires less water to get optimum workability (Khan et al., 2014; Shvarzman et al., 2003).

2.2.1 Fly Ash

Fly ash is a well-known pozzolanic material used to improve the performance of concrete, and serves as replacement material to decrease the amount of cement, which is a beneficial aspect to the environment. It is known as pulverized fuel ash, a by-product of burned coal. Thus, Fly ash has fine particles that function as filler which improves density and minimizes permeability (Xu and Shi, 2018).

2.2.2 Ground Granulated Blast Furnace Slag (GGBS)

This is one of the most widely used pozzolanic materials in cement production, and it is utilized as replacement material for cement. GGBS is a by-product of molten iron and steel industry. It consists mainly of silicate sand and alumino silicates of calcium and of others. GGBS is a highly cementitious material high in CSH, which improves the strength and durability of concrete (Shumuye and Jun, 2018; Siddique, 2007).

- Advantages of using GGBS can include:

- Improving the workability of fresh concrete.
- Enhancing the durability of hardened concrete.
- Increasing the sulfate attack resistance of hardened concrete.

2.2.3 Limestone Powder

Limestone powder is a by-product of aggregate manufacturing. Due to its microstructure, researchers observed that using limestone powder as filler can decrease the porosity and increase the hydration product. On the other hand, it has little effect on the σ_c (Wang et al, 2018; Soroka and Setter, 1977).

2.2.4 Silica Fume

SF is a by-product of silicon metal or alloy production or reduction of quartz to silicon at temperatures around 2000°C. It is known as micro-silica because of the high percentage of silica in its composition reaching 75% and up to 95%, and due to having a particle diameter mainly around 0.1 µm. Unlike other pozzolans, silica fume is very reactive because of its high fineness (Siddique, 2011).

- Advantages of using silica fume may include the following:
  - Creating high bond strength.
  - Improving durability.
  - Achieving high tensile and flexural strength.

2.3 Chemical Admixture

Chemical admixtures are materials added to concrete other than water, cement, and aggregate to give new properties in plastic or curing conditions. Such admixtures include water-reducing or high range water-reducing (plasticizing admixtures), air-entraining admixtures (AEA), pumping aids (lubricating) and viscosity modifying agents (VMA), in addition to accelerators and retarders. Generally, chemical admixtures are manufactured by some chemical processes and cannot be found in nature. Some of the desirable properties of self-compacting concrete include high flowability, deformability, resistance to bleeding and segregation, and a low water/binder ratio. Some admixtures can help to achieve these requirements, such as superplasticizer to decrease water demand, VMA to improve viscosity with low segregation and bleeding tendency, and AEA to improve the stability of air voids inside the mix by increasing bubble adhesion (Şahmaran et al., 2006; Łaźniewska-Piekarczyk, 2012).

2.4 Superplasticizer

This is a kind of chemical admixture that is added to concrete as reducer or high range reducer of water. It improves workability and decreases the w/c ratio, which leads to enhanced strength and durability of the concrete. This enhancement is achieved by spreading the cement particles away from each other and stabilizing the air voids inside the mix, which decreases the water demand. There are many types of superplasticizers based on their chemical composition. New generation superplasticizers work as high range water reducers and viscosity modifying agents (Prakash and Santhanam, 2006), and this is what has been used in the present study.

Felekoğlu and Sarıkahya (2008) conducted experimental study to review the effect of superplasticizer (Polycarboxylate) on the workability of self-compacting concrete. Three types were used in this work: acrylic copolymer, carboxylate-terpolymer, and polyoxyethylene copolymer. The measurements showed that the first type functioned well as a water reducer and was able to impart early strength, but workability was lost faster than in the case of the other two types. These remaining two types worked as high range water reducers and effected excellent workability retention, and they delayed the setting time. The authors conclude that the type of superplasticizer used should depend on site requirements.

Łaźniewska-Piekarczyk (2012) investigated the influence of adding new admixtures on some properties (workability, air entraining, and durability) of SCC. Two types of superplasticizers, VMA and AEA, were used in this investigation. The tests carried out in this study showed that using admixtures clearly affected the fresh and hardened properties of SCC through increasing fluidity of the mix, improving stability, reducing segregation, and enhancing durability. It is preferable to use them together to get the best performance.

2.5 Fibers

Concrete is known to be one of the most widely used materials in construction industry. Nevertheless, at the beginning of the eighteenth century, it became established that concrete is weak under tension forces. Thus, steel bars were used to strengthen tension areas and avoid brittleness. Later, many types of fibers were used such as metallic, organic, and mineral fibers, and randomly distributed fibers were added as second reinforcement to enhance the ductility and improve crack bridging. Some books and articles classify fibers based on their modulus of elasticity into the following groups: (1) High elastic modulus fibers such as steel, carbon, and glass fibers, which can improve flexural strength and impact resistance. (2) Low elasticity fibers such as vegetable and polypropylene fibers, which have negligible effect on post-cracking behavior (Behbahani et al., 2011; Johnston and Colin, 1982).

2.5.1 Steel Fiber

The first research effort that focused on fiber-reinforced concrete was carried out in the USA in the early 1960s. Following these early studies, the American Concrete Institute (ACI) put forward a definition for steel fiber and some limitations on length and aspect ratio. Steel fibers were produced in many shapes (regular and irregular), and more recently, modern shapes have been introduced such as hooked end, straight, and crimped. Adding superplasticizer to the mix was important to improve the workability when steel fibers were included (Naaman, 1985; Rapoport et al., 2002).

- Advantages of using steel fiber may include:
  - Improving the tensile and flexural strengths.
  - Crack bridging and achieving good post-cracking strength.
  - Increasing the ductility of concrete.
  - Enhancing the durability by controlling cracks.

2.6 Fresh Properties and Rheology

According to the American Concrete Institute (ACI), workability of concrete describes the ease of mixing, placement, consolidation or leveling of fresh concrete with minimal loss of mixture homogeneity. On the other hand, rheology of concrete is the experimental study of the flow and deformability of fresh concrete, in other words, it describes the best way to select the type and dosage of chemical and mineral admixtures to improve the workability of concrete. Rheology depends on several parameters that include plastic viscosity and yield stress of fresh concrete mix. Yield stress can be tested by slump test for normal concrete, and slump flow test for high performance concrete, and viscometer and other tests to examine the viscosity of fresh concrete mix (Ferraris et al., 2001).

2.6.1 Effect of Steel Fiber on Fresh Properties of Concrete

Khaloo et al. (2014) examined the influence of adding steel fiber on the rheological (fresh) properties, and mechanical properties of SCC with various volume fractions of 0.5, 1, 1.5, and 2%. Two groups of concrete were cast with different compressive strengths, the first with medium strength and the second with high strength. The study concluded that increasing fiber content reduces both compressive strength and workability based on EFNARC, (EFNARC, 2005).

El-Dieb et al. (2012) concluded from their study that using steel fibers has considerable effect on the filling ability and flow time of SCC. Also, the results of L-box and V-funnel tests were influenced by increasing the amount of fibers, where inclusion of more fibers reduced viscosity and increased segregation. Their work was done by adding steel fiber at four volume fractions in 3 different types of self-compacting concrete. The fiber volumes for type 1 SCC were 0.5%, 1.0%, 2.0%, and 3.0%, whilst, the fiber volumes for both type 2 and type 3 SCCs were 0.5%, 1.0%, 1.5%, and 2.0%.

V-funnel test was carried out by BS EN 12350-9 to assess the viscosity of SCC, and it was observed that increasing the hooked end fibers content caused blockage during the test. Increasing the fiber volume fraction caused an increase in the friction between fibers and aggregates. In addition, it led to an increase in friction amongst the fibers themselves which delayed the time needed to empty the V-funnel (Siddique and Kaur, 2016; Gencel et al., 2011).

Rambo et al. (2014) indicated that the time needed to empty the concrete from the V-funnel was in the range of (6.25-13.37 s) as more steel fibers were added from 0% up to 1.0% by volume. Kamal et al. (2014) noticed that V-funnel time was 10.56, 18.15 s with 1% and 1.5% hooked end straight steel fibers, respectively.

A study by Abbas (2013) was conducted to investigate the influence of adding steel fiber to SCC with 30 mm length and 0.5 diameter, and with fiber volumes ranging between 0.0% and 1.5%. The result of the fresh test showed an increase in the slump flow time, due to the heightened internal friction with increasing fiber content. In addition, the L-box test showed an increase in the rate of blocking and a decrease in passing ability as the fiber volume increased.

2.6.2 Effect of Silica Fume on Fresh Properties and Rheology of Concrete

Using more SF in the mix affects workability, and a maximum reduction of about 5% for slump flow test was shown for specimens that had 14% silica fume as replacement material. In addition, increasing the SF content caused an increase in the V-funnel time by around 25% when SF was added at 14% by cement weight (Benaicha et al., 2015; Mastali et al., 2016).

Lu and Mei (2015) investigated the influence of utilizing silica fume with various percentages (2, 4, 6, 8, 12, and 16%) on slump flow and plastic viscosity of self-compacting concrete. Measurements indicated that viscosity decreased initially, but then started to increase gradually. The variation in the slump flow depended on the viscosity, yield stress, and the time of water addition. Slump flow was affected dramatically by adding 12–16% SF.

2.7 Compressive Strength

One of the standard tests employed to examine hardened concrete properties is the compressive strength test that gives information about the maximum resistance of concrete samples under axial load. The importance of this test comes from the essentiality of this aspect in structural design. Compressive strength is generally measured in newton per square millimeter (N/mm^2), which is equivalent to megapascal (MPa), or pound per square inch (psi). The measurement is usually done after curing for 28 days (Neville, 1995).

2.7.1 Effect of Steel Fiber on Compressive Strength of Concrete

Generally, adding StF to the mixture leads to a reduction in the σ_c due to a corresponding increase in the porosity of the concrete. Khaloo et al. (2014) observed that using fiber at different volumes ranging from 0.5% up to 2% led to a decrease in the σ_c by 4.3% and 18.6%, respectively at 28 days compared to the control mix.

Mohammadi et al. (2008) tested the inclusion of steel fiber in self-compacting concrete. The result showed that steel fiber affects the workability of concrete which causes a decrease in the compaction level of the mix. This point has to be taken into consideration as SCC depends on the action of its own weight and does not require compaction. The authors of the paper indicated that the impact on fresh and mechanical properties depended on the shape and the length of the fibers. In addition, Zeyad (2020) found that the reduction in σ_c of concrete at 28 and 90 days due to the influence of length and shape of hooked end fibers affected the compacting efficiency of the mixture.

Some investigators revealed that adding fibers to concrete led to some change in compressive strength. This variation has been explained by the effect of air trapped in the concrete around the fibers, which decreases the compressive strength of concrete (Pilakoutas et al., 2004).

2.7.2 Effect of Silica Fume on Compressive Strength of Concrete

Substitution of the cement with 8% of SF negatively affects the compressive strength at early ages because it slows the hydration reaction. Nevertheless, it is recognized that SF increases the strength at later ages. When comparing two samples of concrete with and without using SF, it was observed that the presence of SF in the concrete mixture led to a reduction in the σ_c at 28 days after curing up to 19%, 31% and 27% compared to the control mix (Sasanipour et al., 2019).

Pedro et al. (2017) evaluated the mechanical and fresh properties of high performance concrete after the addition of SF. The final results illustrated that replacing cement with 5% and 10% of silica fume caused a reduction of 5% and 16%, respectively, in σ_c at 7 days compared to the control mix without silica fume. Choudhary et al. (2020) observed from their study that using 5% silica fume as utilization material improved σ_c due to the pozzolanic activity and filler behavior between aggregate and sand.

Köksal et al. (2008) performed an experimental study to investigate the effect of hooked end fibers with silica fume on the compressive strength. The fiber was added at l/d of 80 and 65, and two different volume fractions of 0.5% and 1%. Three replacement ratios of silica fume (0, 5, 10 and 15%) by weight of cement were applied. The outcome was a clear increase in σ_c with increasing SF content, where the highest increase was 85.5% by 15% of silica fume only. Using both silica fume and hooked end fibers produced greater strength than the mix which had just silica fume.

2.8 Splitting Tensile

2.8.1 Effect of Steel Fiber on Tensile Strength of Concrete

Even though concrete is weak under tension, it is common to estimate the tensile strength of concrete because it gives an indication of the quality and durability of the mix. This is done by applying an indirect load on cylindrical samples up to ultimate fracture. The importance of this test stems from the problem of cracking due to shear stress and shrinkage effect, which reduce the durability of concrete (Neville, 1995).

Aslani et al. (2013) performed a study to determine the influence of steel and polypropylene fibers on compressive and tensile strength of SCC. The study included four SCC mixes: plain SCC, steel, polypropylene, and steel-polypropylene. The average σ_s of the mix with StF was 23%, 27%, and 15% higher than the corresponding mixes without these fibers, namely, plain SCC, polypropylene and steel-polypropylene, respectively. These outcomes indicated the improvement of tensile strength for SFR-SCC.

Moreover, a study was done by Gencel et al. (2011) to determine the influence of using StF on the workability and mechanical properties of SCC. The fiber contents used were 15, 30, 45, and 60 kg/m^3 with a length of 30 mm. The presence of steel fibers increased the σ_s by 18.6, 23.3, 14.0, and 21% respectively, hence, the highest increase was with the second mix.

2.8.2 Effect of Silica Fume on Splitting Tensile Strength of Concrete

The experimental research done by Mastali et al. (2016) illustrated an enhancement of the σ_s strength by SF due to improvement in both paste-aggregate and matrix-fiber bond properties. In addition, using silica fume as a replacement material improved load carrying capacity of SCC. On the other hand, the improvement in deflection up to ultimate load carrying and post-cracking strength was negligible.

2.9 Flexural Strength

This test is performed by applying a two-point symmetrical load on unreinforced beam until failure happens. The space between these two loads will be under tensile force until cracking takes place. This test is important when steel fiber is added to concrete because of its role in improving ductility and bridging the crack (Neville and Brooks, 1987).

2.9.1 Effect of Steel Fiber on Flexural Strength of Concrete

Researchers examined the effect of adding steel fiber of various lengths (35–50 mm) on the flexural test result of reinforced self-compacting concrete. Studies revealed that the spreading of long fibers in one dimension improved the flexural strength more than the spreading of short fibers in the three-dimensional orientation (Ponikiewski et al., 2013; Mastali et al., 2015).

Abbas (2013) observed that inclusion of steel fiber in SCC at 0.0%, 0.5%, 0.75%, 1%, and 1.5% volume fractions clearly improved flexural strength. The highest increase achieved was double the flexural strength for the control mix with 1.5% fiber.

Turk et al. (2021) investigated the effect of using micro and macro steel fibers on the flexural strength of hybrid (SFR-SCC). Beams of 100×100×400 mm dimensions were prepared for the test. The outcome was an improvement in the flexural strength with increasing macro fibers volume. The highest increase was 13 MPa achieved with 1.5% macro fiber volume, while the micro fibers had little influence on the flexural strength because they could not bridge the macro cracks.

2.9.2 Effect of Silica Fume on Flexural Strength of Concrete

Bhanja and Sengupta (2005) indicated that flexural strength was significantly enhanced, by increasing SF replacement percent, where the optimum percent was found to be 15%. Five mixes were prepared to examine the influence of the addition of SF on tensile and σ_f of HPC. The mixes had different w/c ratios (0.26, 0.30, 0.34, 0.38, and 0.42) with partial addition of silica fume by 0%, 5%, 10%, 15%, 20% and 25% of cement weight.

2.10 Durability

2.10.1 Effect of Steel Fiber on Durability of Concrete

An experimental study was conducted by Zhang et al. (2019) to investigate the durability of steel fiber reinforced concrete (SFRC) with nano-silica particles at constant w/c around 0.29. Crimped steel fibers of 32 mm length and 40 l/d ratio were used at five volume dosages of steel fiber of 0, 0.5, 1.0, 1.5, 2, and 2.5%. It was concluded from the measurements that addition of more steel fiber to the concrete had a negative effect on the permeability, which decreases the durability as well. Moreover, a research study was performed by Hubert et al. (2015) to see the influence of various fiber V_f on the permeability of reinforced concrete. In this study, StF were added at volumes of 0, 0.75, 1.5, and 2%. The experiments demonstrated that adding steel fiber to normal concrete might increase the permeability due to not having enough paste to warp the fiber and the aggregate, which leads to the formation of small cracks that water can penetrate. Otherwise, increasing the fiber content in HPC or ultrahigh performance concrete resulted in a decrease in the permeability, and an enhancement in performance.

On the other hand, another study observed that hydraulic concrete containing steel fiber showed a reduction in the permeability of concrete, and enhanced elastic modulus and tensile strength, and controlled cracks (Huang and Xie, 2011).

2.10.2 Effect of Silica Fume on Durability of Concrete

One study found that substitution of cement with 8% SF by content in SCC can decrease water absorption and porosity. Furthermore, the measurements of rapid chloride penetration test revealed that silica fume had an effective role in controlling chloride penetration. This was due to the control of silica fume over the temperature of the reaction with the solutions in the test, which lead to controlling charge movement during the test (Sasanipour et al, 2019).

Santos et al. (2019) mentioned in their study that using minerals such as SF and fly ash can potentially enhance the durability of concrete, including porosity and resistance to chloride ion penetration. Moreover, Kapoor et al. (2016) performed a study to explore the impact of mineral admixtures on the durability of self-compacting concrete. The outcome showed that using 10% SF as a replacement material decreased the water penetration depth and enhance the durability.

Yazıcı (2008) concluded that high performance self-compacting concrete can be obtained using high content of fly ash and 10% of SF as replacement material. After adding fly ash and SF, the concrete mixture demonstrated desirable behavior regarding mechanical properties, freeze and thaw resistance, and resistance against chloride ion penetration.

2.11 Impact Resistance

Generally, FRC has higher ductility than normal concrete because adding fiber enhances the performance of concrete under dynamic loading. Many test methods are available for the measurement of the IR of FRC, but they are expensive, complicated, and time consuming. The drop weight impact resistance test was developed by the ACI committee to determine impact resistance of FRC after making some adjustments to the aggregate impact test machine based on the BS 812: part 112 standard (Eren et al., 1999).

Nili and Afroughsabet (2010) conducted a study to investigate the effect of adding steel fiber with silica fume on the impact resistance of concrete. The w/c ratios used in the study were 0.36 and 0.46, with hooked end steel fibers of 60 mm length and 80 l/d at V_f of 0.0, 0.5, and 1%. The result revealed that increasing the fiber content increased the number of blows needed to make the first crack in the concrete. Adding hooked fibers at 0.5 and 1% in mix A1 delayed the first crack until the 10th and 12th blow respectively, whereas inclusion of silica fume at 8% enhanced the impact resistance for both mixes due to its role in increasing the brittleness of the concrete.

Abid et al. (2020) carried out a study to determine the influence of micro straight fiber on the impact resistance of SCC employing the repeated drop-weight impact test. Various fiber contents (0%, 0.5%, 0.75%, and 1%) by volume were used with different w/c ratios. The results revealed that increasing the fiber volume fraction enhanced the impact resistance.

Chen et al. (2011) evaluated the use of steel fiber reinforced with main steel rebar on impact resistance of concrete. Steel fiber had a length of 35 mm and an l/d of 64. Six mixes were prepared in this work: a control mix, two mixes with 20 kg and 35 kg of fibers, a mix with steel bars only, and the last two mixes had steel bar with 20 kg and 35 kg of steel fiber. The results showed that using steel fibers had a significant effect on impact resistance, especially regarding the first crack which is an important aspect of achieving high quality concrete.

2.12 Ultrasonic Pulse Velocity

2.12.1 Effect of Steel Fiber on Ultrasonic Pulse Velocity

Gencel et al. (2011) investigated the workability and hardened properties of SCC with different hooked end fiber contents. The rate of pulse velocity decreased in the samples which had steel fiber, possibly because of the increase in the voids blended with fibers as compared to plain concrete. In addition, randomly distributed steel fibers in cube samples caused the waves to deviate to other directions, which means that the waves did not follow a straight line across to the other end of the cube.

AL-Ridha et al. (2020) stated that UPV increased with increasing the amount of steel fiber in both cubic and cylindrical samples. This behavior may be attributed to faster wave transfer in the metal relative to the concrete. The amounts of steel fiber used were 0.0, 0.4, and 0.8% by volume of concrete.

Sanjeev and Nitesh (2020) conducted a study to determine the effect of using StF and glass fiber on the hardened properties of SCC. In this work, steel fiber of 35 mm length was added at different V_f (0.3, 0.6, and 0.9%). The measurements showed that pulse velocity declined as the fiber content increased.

2.12.2 Effect of Silica Fume on Ultrasonic Pulse Velocity

Ulucan et al. (2008) performed an experimental study to investigate the influence of mineral admixtures on pulse velocity and σ_c of SCC. They used different proportions of silica fume of 5% and up to 20%. Ultrasonic velocity test done at 3, 7, 28, and 130 days showed an increase in pulse velocity as silica fume increased. This improvement resulted from the formation of calcium hydrate silicate (C-S-H). The highest result was achieved with 10% replacement at 28 and 130 days.

Another group of researchers investigated the effect of substituting cement content by 8% SF on some properties of concrete. Four mixes were prepared with different recycled aggregate content and constant silica fume volume. The results revealed that silica fume decreased the velocity of the pulse in ultrasonic velocity test. The reduction in the pulse wave velocity might have been due to the lighter density of SF compared to cement (Sasanipour et al., 2019; Popovics et al., 1990).

Chapter 3

METHODOLOGY – EXPERIMENTAL STUDY

3.1 Introduction

This chapter presents information about the materials that were used in this research and explains the experimental procedures in detail. Furthermore, it contains an explanation regarding mix preparation, casting, curing, and testing methods.

3.2 Materials

The materials used in this experimental work are defined in the following sections:

3.2.1 Cement

CEM II Portland-slag cement of 42.5 grade was used in this study. The chemical composition of the cement is presented in Table 1.

3.2.2 Silica Fume

The SF used in this research was obtained from silicon metal industry, and used as additive in this study to improve microstructure and consistency of the concrete. The maximum size of the particles was 1 µm in diameter. The chemical composition of silica fume is shown in Table 1, and silica fume is illustrated in Figure 1.

Figure 1: (a) Limestone (b) Silica fume

3.2.3 Limestone

Limestone powder was collected from the industrial area in Turkey, and it was used as filler material. The maximum size of the particles was 0.6 mm in diameter. The chemical composition of limestone is shown in Table 1. Limestone is illustrated in Figure 1.

Table 1: Chemical composition (in percent) of cement, silica fume, and limestone

Oxide Compound	Cement	Silica fume	Limestone powder
SiO_2	29.82	92.55	0.25
CaO	57.43	2.36	69.13
Al_2O_3	5.88	-	-
Fe_2O_3	2.47	0.79	0.09
MgO	3.46	0.15	17.42
$CaCO_3$	-	-	95.00

$MgCO_3$	-	-	-
SO_3	2.64	0.52	0.51
Free CaO	1.09	-	-

3.2.4 Mixing Water

Tap drinking water free of harmful substances, such as alkalis, acids, oils, and organic materials, was utilized for mixing and curing in this study.

3.2.5 Fine Aggregate

Fine aggregate used in this study was well-graded crushed limestone from Beşparmak Mountains of Cyprus with a maximum diameter of 5 mm. The gradation test for fine aggregate was carried out in accordance with ASTM C33 specifications. Sieve analysis of fine aggregate is presented in Figure 2.

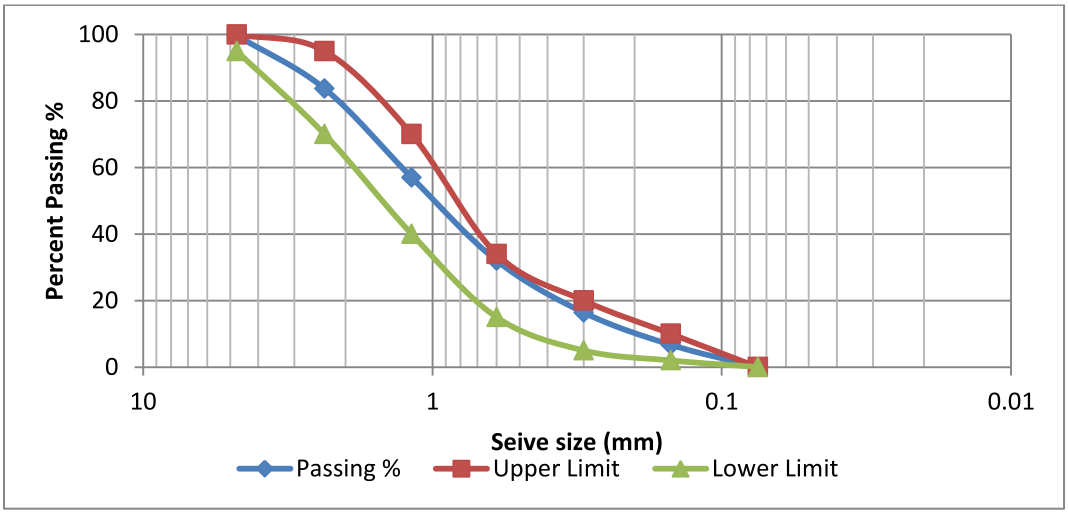

Figure 2: Sieve analysis of fine aggregate

3.2.6 Coarse Aggregate

Crushed limestone from Beşparmak Mountains of Cyprus with a maximum diameter of 12.5 mm as recommended was utilized in this research. The gradation values for the coarse aggregate were obtained after testing it in the lab according to ASTM C33 specifications.

3.2.7 Superplasticizer

Superplasticizer in this study is an effective water-reducing admixture which enhances concrete workability. According to ASTM C494, Sika® ViscoCrete® (Hi-Tech 51) is a third generation concrete and mortar additive used as high range water reducing admixture and viscosity modifier, which also helps maintain workability for a long time. The chemical structure of Sika® ViscoCrete® is a modified polycarboxylate-based polymer.

3.2.8 Reinforcing (Steel Fiber)

The effect of Dramix® 3D glued steel fibers on the fresh and hardened state of SCC was investigated. The fibers had 60 and 80 aspect ratios, and are illustrated in Figure 3, and their properties are detailed in Table 2.

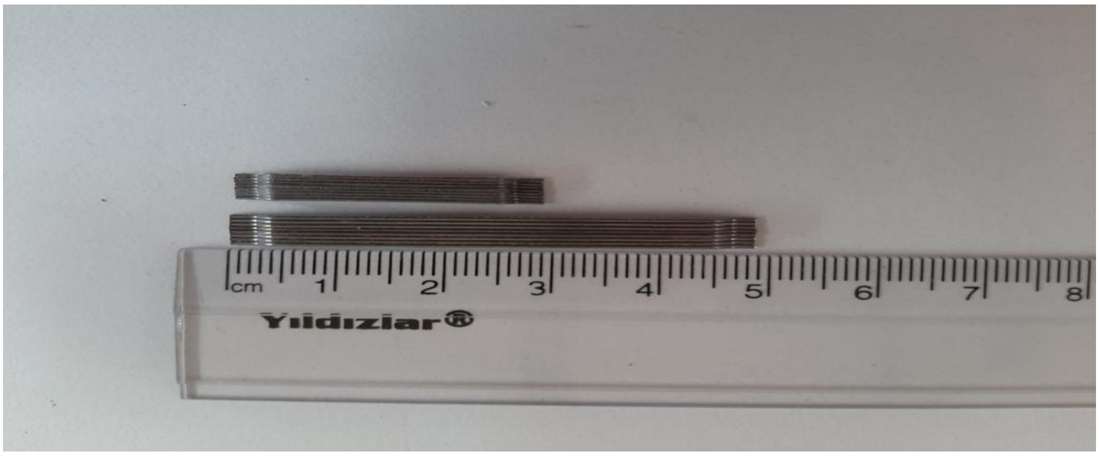

Figure 3: Hooked end steel fibers with 60 and 80 aspect ratio

Table 2: Fiber properties and shapes

Fiber Types	**Fiber Family**	**Length L (mm)**	**Diameter D (mm)**	**Aspect ratio (l/d)**
60/30 BG	3D	30	0.5	60

80/50 BG	3D	50	0.625	80

B: Bright and G: Glued.

3.3 Trials

To obtain the most desirable mix, several trials were conducted and the mixes were tested based on the EFNARC specification and guidelines for SCC, EFNARC, (2005) . Some techniques were used to achieve the desired mix: Firstly, the coarse aggregate (crushed limestone), size range: 5-12.5 mm content was decreased to reduce the inter-particle friction. Secondly, silica fume and limestone dust were added to the mix in order to increase the paste, enhance the viscosity, and lubricate the solid particles. Thirdly, ViscoCrete superplasticizer was used at 1.4-0.40% from the binder content (cement, silica fume and limestone powder) to improve the workability with low w/b ratio, and control the stability of the mix. Finally, the fine aggregate was decreased somewhat to justify the fresh properties, and keep the w/b ratio low around 0.35 by using superplasticizer.

Table 3 illustrated the different trials in details before obtained the optimum mix design. First, the mix was designed as normal concrete with high slump to give an indication about the materials content, but it was not enough even after using superplasticizer (Glenium). The mix behave like a liquid with low viscosity. After that steel fibers added to the matrix with different lengths, l/d and V_f to investigate if the mix will get the SCC criteria of fresh properties (flowability, filling ability and passing ability), the several SCC mixes failed to pass the requirements for fresh properties, even after making some adjustments on the coarse and fine aggregate contents, the consistency of the mix was low with high tendency for blocking and segregation. To solve these problems based on EFNARC specification and trials (behavior of the mix), new superplasticizer ViscoCre-te® (Hi-Tech 51) was used to improve the stability and viscosity of the mix, and powder content was increase by adding limestone powder and silica fume to enhance the cohesiveness between the particles and to increase the paste content to envelope the different particles beside that decrease the inter friction inside the matrix. Before finalize the work on the trials the cement type was changed from type three (high early strength) to CEM II Portland-slag cement as the workability of the mix was quickly lost due to the high hydration reaction with cement type three. The fiber content was selected based on the trials as shown 0.35%, 0.45% and 0.55% V_f , to get the most desirable mix with high fresh performance and hardened properties.

Table 3: Trials conducted in order to achieve the desired mix

Trial No.	**Ceme -nt kg/m³**	**Lime-stone kg/m³**	**Silica-Fume kg/m³**	**Water kg/m³**	**Fine Agg kg/m³**	**Coarse Agg kg/m³**	**SP %**	**Steel Fiber %**	**Super plastic-izer**	**length of fiber mm**
1	368	0	0	272	1077	634	0	0	_	_
2	368	0	0	270	1077	636	1.0	0	Gleniu-m	_
3	368	0	0	268	1077	636	1.2	1	Gleniu-m	60
4	368	0	0	268	1077	636	1.0	0.75	Gleniu-m	50
5	368	0	0	268	1077	636	1.3	0.75	Gleniu-m	30
6	450	0	45	200	891	822	1.20	0.75	Gleniu-m	30
7	400	120	40	170	920	500	1.4	0.50	Visco-Crete® (Hi-Tech 51)	30
8	400	120	40	170	920	500	1.5	0.50	Visco-Crete® (Hi-Tech 51)	30

9	400	120	40	170	920	500	1.6	0.50	Visco-Crete® (Hi-Tech 51)	30
10	400	140	20	180	920	490	0.7	0.50	Visco-Crete® (Hi-Tech 51)	50
11	400	150	10	185	910	500	0.5	0.5	Visco-Crete® (Hi-Tech 51)	50
12	400	152	8	190	900	500	0.4	0.5	Visco-Crete® (Hi-Tech 51)	50
13	400	152	8	190	906	497	0.45	0.55	Visco-Crete® (Hi-Tech 51)	50

3.4 Mix Design Proportioning

According to the trials based on EFNARC specification and guidelines for SCC detailed above, the mix design of SCC was prepared as shown in the following Table 4, Concrete, S. C. (2005).

Table 4: Mix proportions

Mix Type	**Cement** **kg/m^3**	**LS** **kg/m^3**	**SF** **kg/m^3**	**Water** **kg/m^3**	**Fine** **kg/m^3**	**Coarse** **kg/m^3**	**SP** **%**	**Fiber** **kg/m^3**
Control	400	152	8	190	906	497	0.45	0
60 l/d, 0.35%	400	152	8	190	906	497	0.45	27.48

60 l/d, 0.45%	400	152	8	190	906	497	0.45	35.33
60 l/d, 0.55%	400	152	8	190	906	497	0.45	43.18
80 l/d, 0.35%	400	152	8	190	906	497	0.45	27.48
80 l/d, 0.45%	400	152	8	190	906	497	0.45	35.33
80 l/d, 0.55%	400	152	8	190	906	497	0.45	43.18

To investigate the performance of SFR-SCC, seven mixes were considered. In each series, the proportions of cement content, fine and coarse aggregate, water, superplastiscizer, silica fume, and limestone powder were kept constant, while the fiber content by volume of concrete mix was changed as shown in Figure 4. Control mix, series A had 60 l/d hooked end steel fiber, and series B had 80 l/d hooked end steel fiber.

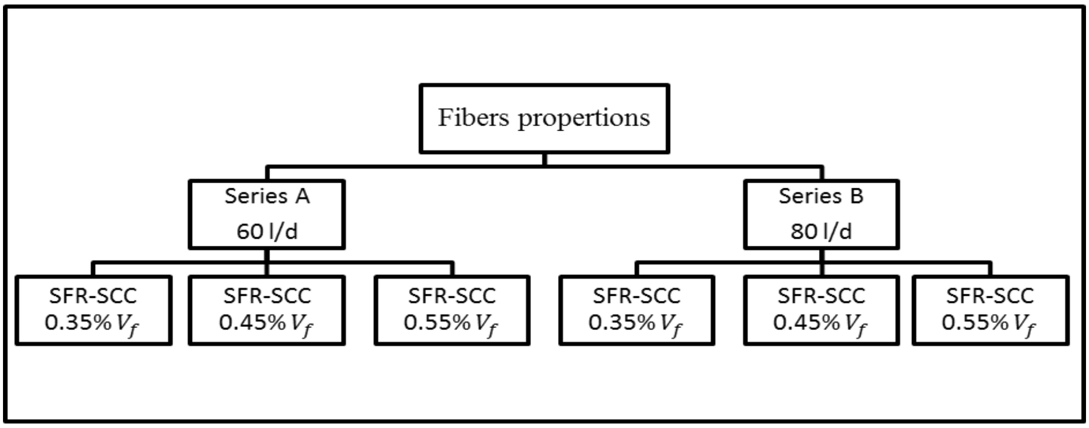

Figure 4: Fiber volume fractions used for reinforcing SCC

3.5 Mix Procedure

The mix was prepared by mixing coarse and fine aggregates for 1 min, followed by the addition of silica fume, limestone powder and finally cement, and everything was mixed for 2 minutes more. Two thirds of the superplasticizer was added to the water to fluidize the dry mix, which was then mixed for around 2 minutes. Next, the remaining superplasticizer were added. At the end, steel fiber was added gradually in order to prevent ball formation. The mixing process is presented in Figure 5.

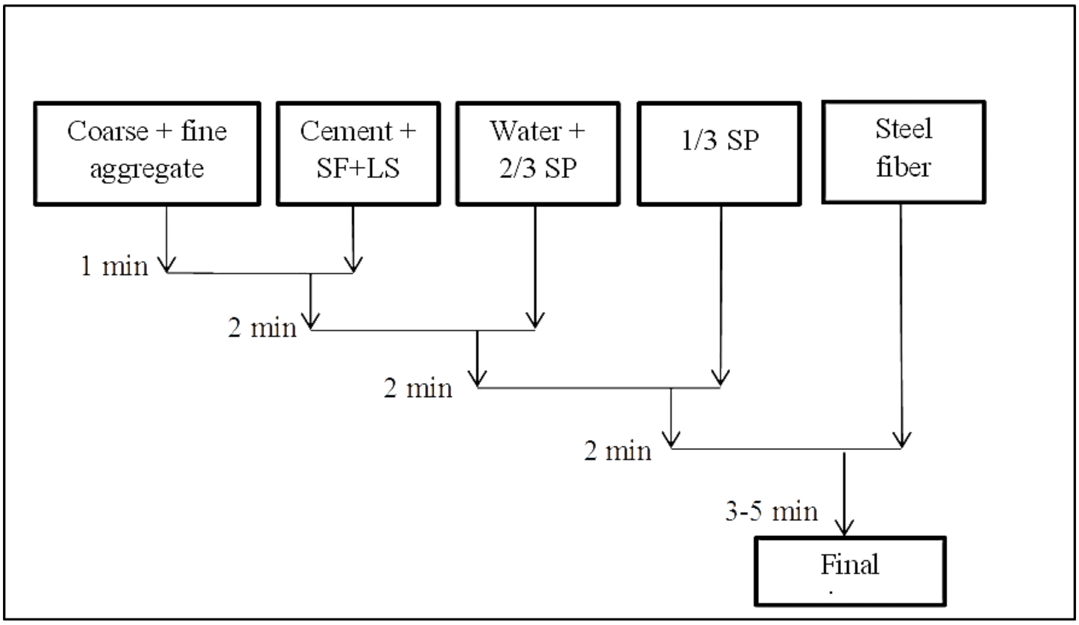

Figure 5: Mixing procedure

3.6 Casting and Curing

Four different types of samples were casted for each mix as shown in Figure 6: twelve cubes of 150 mm, 3 beams of 100×100×500 mm size, three cylinders of 100×200 mm size, and one cylinder of 150×300 mm size. The molds were cleaned and then oiled to facilitate the demolding of samples. After casting the samples, the molds were kept in the curing room directly for 24 hours at 98% relative humidity and 23^{o}C as there was no need to vibrate the concrete. Then, the samples were removed from the molds and put again in the curing room with the same conditions until testing time.

Figure 6: Self-compacting concrete samples

3.7 Test on Fresh Concrete

3.7.1 Slump Flow Test

This test is used to measure the ability of fresh SCC to flow based on EFNARC specification and guidelines for SCC. The results of this experiment give indications regarding the flowability and segregation tendency as shown in Figure 7. The mean of final diameter of expanded concrete in two directions was calculated, and the mix was categorized according to the criteria in Table 5 below:

Table 5: Slump-Flow classes, EFNARC, (2005)

Class	**Slump-flow in millimeters**

SF1	550 to 650
SF2	660 to 750
SF3	760 to 850

SF1: low flowbility, SF2: medium flowability, and SF3: high flowability.

The result was calculated by applying equation (1):

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

Where

SF: Slump flow in millimeter.

d_1: The largest diameter of concrete flow spread in millimeter.

d_2: The largest diameter of concrete flow spread perpendicular to d_1 in millimeter.

Figure 7: Slump-flow test

3.7.2 V-funnel Test

Based on EFNARC specification and guidelines for SCC, this test is used to determine the V-funnel flow time for fresh concrete in order to examine the viscosity and filling ability of SCC with a maximum coarse aggregate size of 20 mm. It is carried out by filling the V-funnel with fresh mix which is left to rest around 10 s, and then a small gate is opened to discharge the concrete under its own weight. The time required to empty the V-funnel is measured. The stable discharge time is between 6–12 s. The viscosity of fresh SCC was classified according to Table 6:

Table 6: Viscosity classes, EFNARC, (2005)

Class	**V-funnel time in seconds**
$VF1$	≤ 8
$VF2$	$9\ to\ 25$

VF1: low viscosity, and VF2: high viscosity.

3.7.3 L-box Test

This test was carried out according to EFNARC specification and guidelines for SCC. L-box test determines the passing ability ratio of SSC, and the resistance to segregation due to passing the bars. The test apparatus was filled with fresh mix, and then the sliding gate was opened to allow the concrete to flow from the vertical to horizontal section. The height of the concrete was measured in the two sections to calculate the blocking ratio H_2/H_1, which gives an indication about the passing ability and segregation tendency. Passing ability was determined according to the criteria in Table 7:

Table 7: Passing ability classes (L-box), EFNARC, (2005)

Class	Passing ability
PA1	≥ 0.8 with 2 rebars
PA2	≥ 0.8 with 3 rebars

3.8 Tests on Hardened Concrete

3.8.1 Compressive Strength Test

For each mix, nine cubes were prepared with 150 mm edges to analyze the σ_c of SCC. The effect of steel fiber and silica fume at 3, 7, and 28 days was investigated according to BS EN 12390-3:2009 standard shown. The average of the three values at different ages were calculated and reported.

3.8.2 Split Tensile Strength Test

Cylindrical samples were prepared with dimensions of 100×200 mm to determine the influence of steel fiber and silica fume after 28 days of curing under laboratory conditions. The test procedure was done according to ASTM C496/C496M – 17.

3.8.3 Flexural Strength Test

In order to determine the σ_f of hardened SCC, 3 beams with dimensions of 100×100×500 mm were cast for each mix. The prepared specimens were tested at age 28 days and the mean of the result was calculated as the flexural strength. For flexural toughness, the first step was to obtain the force-deflection curve using the control testing machine through applying a constant load of 0.05 mm/min up to 3 mm deflection as the recommended standard as shown in Figure 8. The area under the curve was then calculated using Originpro8 program, and was taken to represent flexural toughness. The experimental procedure for this test was performed based on ASTM C1609/C1609M-19a. The maximum capacity of the testing machine was 200 kN.

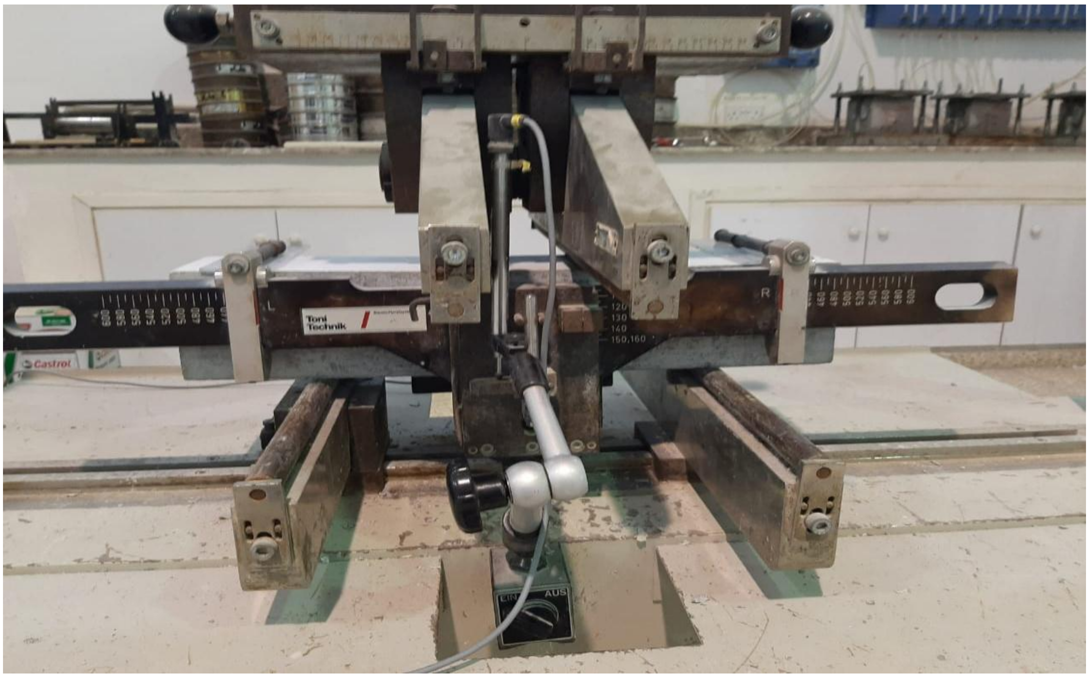

Figure 8: Flexural strength test

3.8.4 Ultrasonic Pulse Velocity Test

UPV is one of the non-destructive tests used for quality control of various concrete members. The same samples that were prepared for compressive strength test above were usable also for this test. This test involves calculating the velocity of the pulse wave passing through the concrete sample. The time taken by the pulse to transit between the two transducers at the two sides of the sample is measured. The process is illustrated in Figure 9. The test was performed according to ASTM C597.

The pulse velocity was calculated using equation (2):

$$V = \frac{L}{T}$$

Where:

V: Pulse velocity in km/s.

L: distance between transistors in meters.

T: transit time in seconds.

The concrete was classified based on Table 8 below:

Table 8: Classification of concrete quality ratings based on UPV test BS 1881: Part 203

Class	**Velocity (km/s)**
Excellent	> 4.5
Good	3.50-4.50
Doubtful	3.0-3.50
Poor	2.0-3.0
Very poor	<2.0

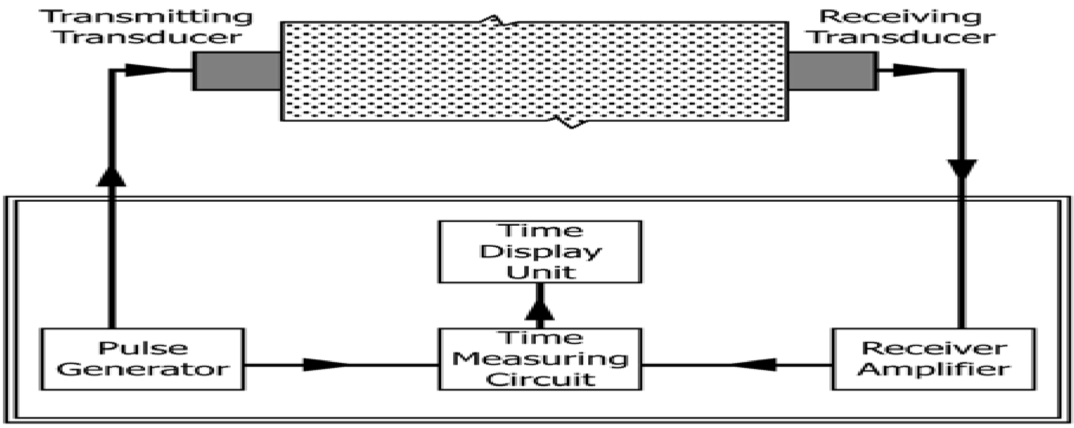

Figure 9: Schematic of pulse ultrasonic velocity apparatus, (ASTM C 579-02, 2003)

3.8.5 Schmidt Hammer Test

This test was conducted based on ASTM C805/C805M–18. The method determines the dimensionless rebound number of hardened concrete by using a spring-driven steel hammer. The resulting number is converted using a specific chart to give a measurement of the strength of concrete and hardness at the surface of concrete. This test was done by compressing a metal plunger which was in contact with the concrete surface to give the rebound number readings on the scale.

3.8.6 Impact Resistance Test

The repeated impact drop-weight test according to ACI committee standards is based on the number of blows necessary to cause the first crack and ultimate failure in the specimen (ACI Committee 544, 1996). This number of blows is used to estimate the energy absorbed by the cylindrical sample up to failure. We used this test to demonstrate the improvement achieved after adding fibers to the concrete. For this purpose, three specimens with dimensions of 150×63 mm were obtained by cutting the cylinder specimen into equal pieces as shown in Figure 10. The cylinder samples were placed in the test machine and the load was applied by dropping a hammer weighing 13.5 kg from a height of 300 mm onto the specimen. The setup is presented in Figures 11 and 12.

The impact energy was calculated using equation (3):

Impact energy (J) = 0.5 x m x v^2 x N

Where:

m : mass of the hammer.

V: the velocity of the hammer when its hit the sample (Instantaneous) 1.8088 m/s, Marar et al., (2001).

N: number of blows up to ultimate crack.

Figure 10: Cutting machine used to prepare impact test samples

Figure 11: Impact resistance test of the sample

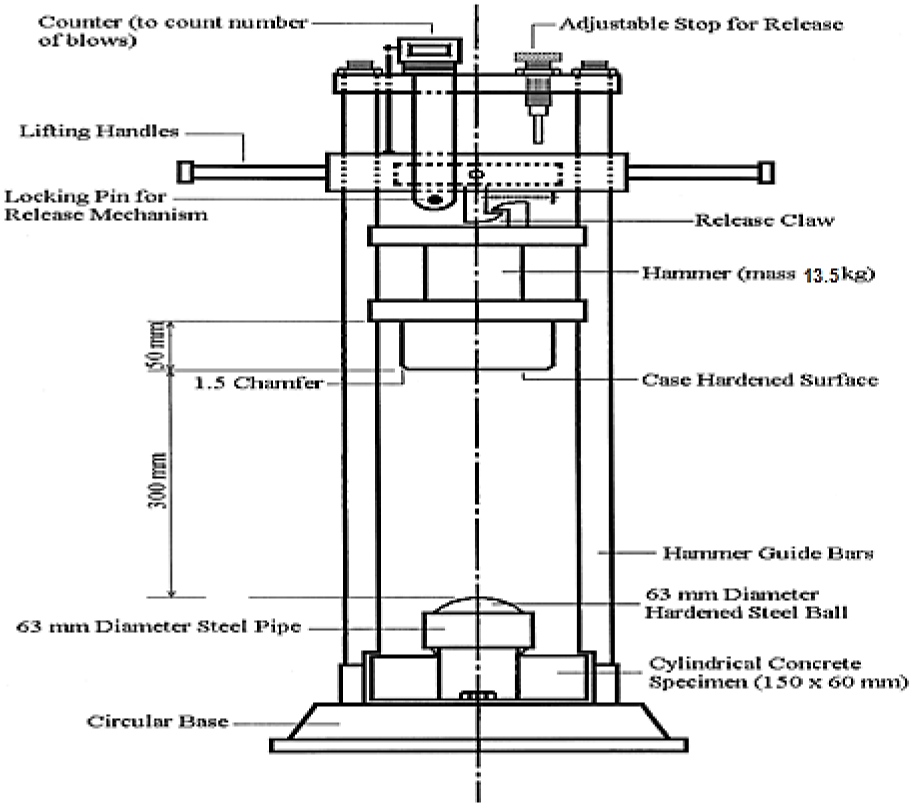

Figure 12: Impact resistance test apparatus, Eren et al., (1999)

3.8.7 Permeability Test (Water Penetration)

When water comes into the concrete and contacts the reinforcing steel, it causes corrosion, and this in turn causes a rust layer to appear. Consequently, tensile forces are generated due to expansion of the oxide causing the concrete to crack and delaminate. Thus, this test method is used to give an indication about the durability of concrete. It is carried out by measuring the penetration depth of the water inside the specimen under constant water pressure of 500 kPa for 72h after at least 28 days of curing according to European Standard (EN 12390-8:2009). This is illustrated in Figures 13 and 14. Three cubes with 150 mm sides were prepared for this experiment.

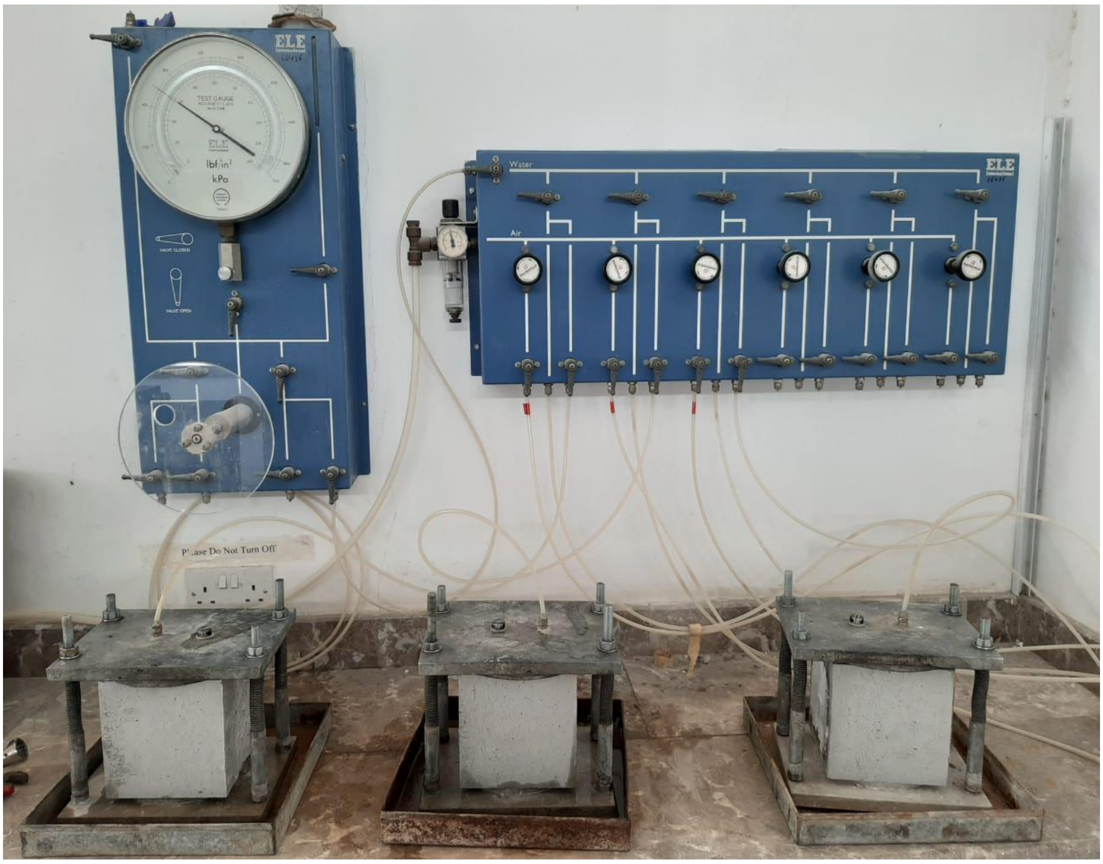

Figure 13: Permeability test

Figure 14: Splitting the samples to measure water penetration depth

Chapter 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter includes the experimental results and critical discussion for seven different mixes for the purpose of studying the effect of adding steel fibers and silica fume on the performance and properties of SCC. The following tests will be discussed; for fresh concrete: slump flow, V-funnel, and L-box test, for hardened concrete: compressive, flexural and tensile strength tests, impact resistance and permeability test, and finally, non-destructive tests: rebound hummer and ultrasonic velocity test. After analyzing the results and outcomes using Excel 2010, they were arranged in tables and illustrated in graphs for better understanding.

4.2 Fresh Properties (Workability)

The results show that SCC mixes had no significant problems in filling ability, flowability, segregation resistance, and passing ability when the steel fibers were added to the mixture. Fresh test results are presented in Table 9, and classified in Table 10 according EFNARC specification and guidelines for SCC. The parameters in Table 10 were explained in detail in the previous chapter.

Table 9: Effect of adding steel fiber on fresh mix properties of SCC

Test	**Control**	**60 l/d, 0.35%**	**60 l/d, 0.45%**	**60 l/d, 0.55%**	**80 l/d, 0.35%**	**80 l/d, 0.45%**	**80 l/d, 0.55%**

Slump flow (mm)	760	750	740	735	740	730	725
Change%	_	-1.3	-2.6	-3.3	-2.6	-3.9	-4.6
V-funnel (second)	4.5	5.4	6.2	7.3	6.9	7.2	8
Change%	_	20	37.8	62.2	52.2	58.9	77.8
L-box	1	0.95	0.94	0.92	0.93	0.89	0.84
Change%	_	-5.0	-6.0	-8.0	-9.0	-11.0	-16.0

Table 10: Classification of the different mixes of SCC based on EFNARC specification and guidelines for self-compacting concrete

Test	**Control**	**60 l/d, 0.35%**	**60 l/d, 0.45%**	**60 l/d, 0.55%**	**80 l/d, 0.35%**	**80 l/d, 0.45%**	**80 l/d, 0.55%**
Slump flow (mm)	SF3	SF2	SF2	SF2	SF2	SF2	SF2
V-funnel (Second)	VF1	VF1	VF1	VF1	VF1	VF1	VF1
L-box	PA1	PA1	PA1	PA1	PA1	PA1	PA1

The results in Table 9 illustrate that although the addition of fibers slightly reduced the slump flow value the sufficient workability concrete is attained at each fresh mix. It was obvious that when the V_f of steel fibers increased from 0.35% up to 0.55%, the average of spread diameter and passing ability of fresh SCC decreased for the two different fibers. This indicates that adding StF increases the possibility of blocking, increases the friction between the particles, and delays the time needed to empty the V-funnel. Khaloo et al., 2014; El-Dieb et al., 2012; Siddique and Kaur, 2016; Gencel et al., 2011 all reported the same behavior when fibers were added to SCC.

In addition, the workability decreased as the l/d of steel fibers increased, for example, the V-funnel time increased 20% for the 60 l/d 0.35%, and 52.2% for the 80 l/d 0.35%, compared with the control mix. This highlights the challenge of mixing and placing the concrete with longer fibers. Ghanem and Obeid, (2015) found similar results. Using silica fume as additive, the improvement in the viscosity of fresh concrete was not noticed due to the low content but it enhance the consistency of the matrix. The most negative effect on the fresh properties, especially in the case of L-box test, was with 80 l/d 0.55% fiber for the reasons mentioned above. All this behavior is explained clearly in Figures 15-17.

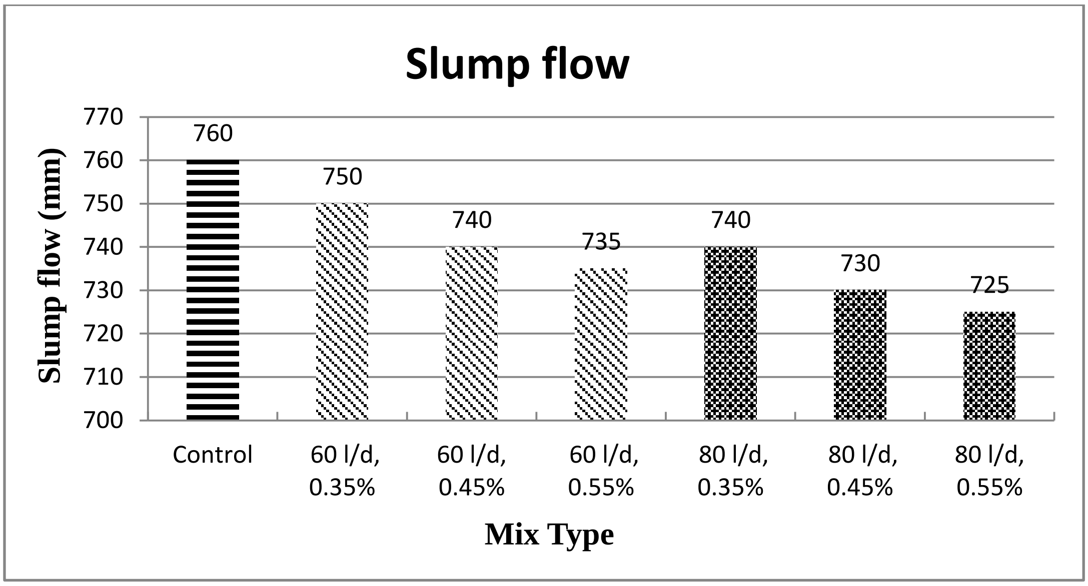

Figure 15: Slump flow test results

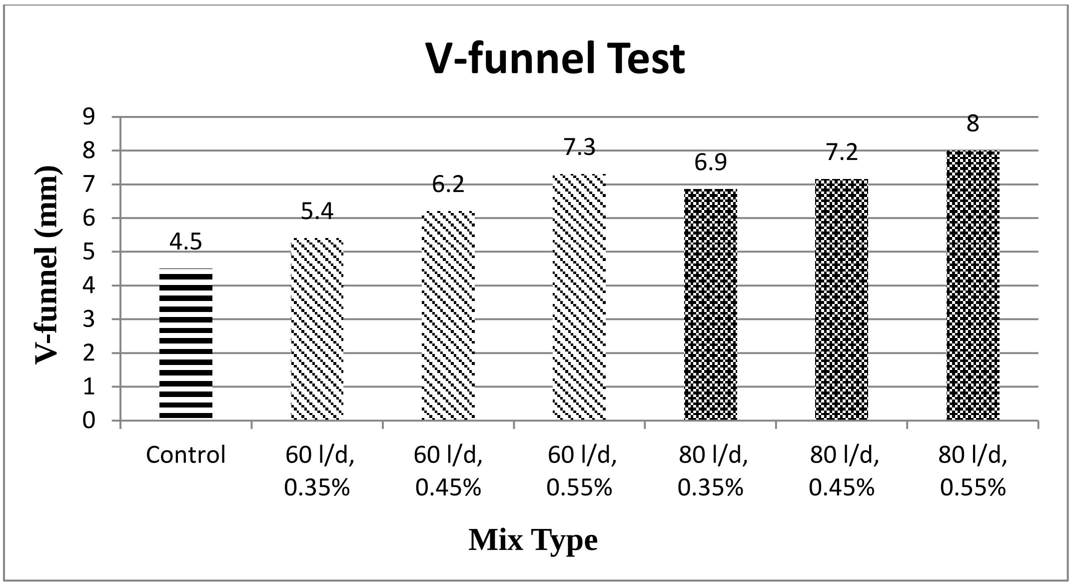

Figure 16: V-funnel test results

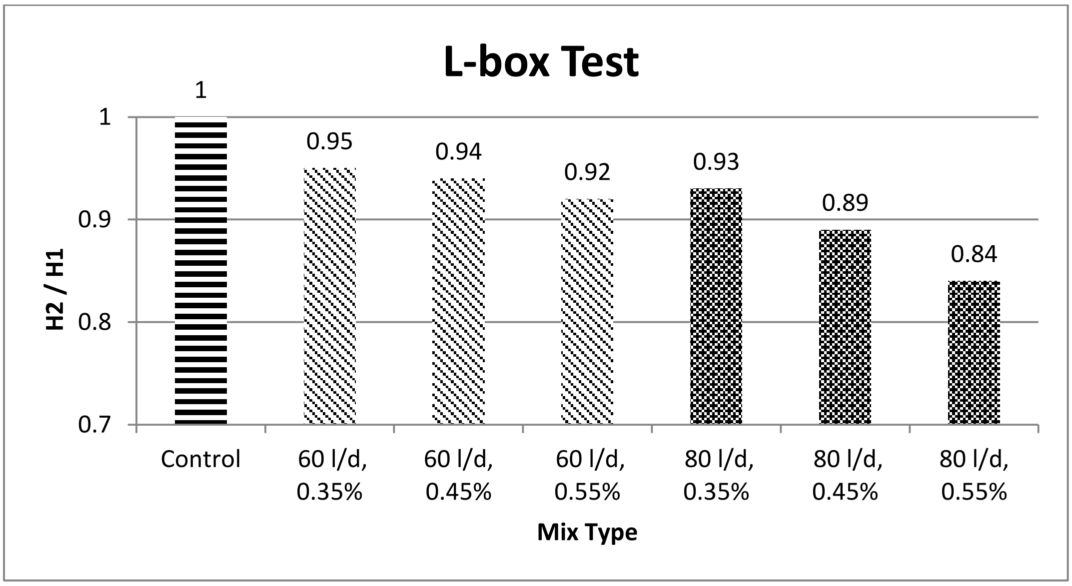

Figure 17: L-box test results

4.3 Ultrasonic Pulse Velocity and Rebound Hammer Test

The Non-destructive tests were conducted to evaluate the quality (homogeneity) and surface hardness of SFR-SCC cube samples at 28 days according to European Standard (EN 12390-8:2009) and ASTM C805/C805M –18 respectively.

The rebound hammer and UPV test values of SFR-SCC with classification of the quality of concrete are shown in the Table 11 and Table 12. It can be seen that the surface hardness of the different mixes was of the hard layer class. The pulse velocity of the mixes that had StF decreased as the V_f of the fibers increased compared to the control mix. Generally, the homogeneity of the mixes was lower than that of the control mix due to the effect of the fiber on the uniformity of the mixture, entrapped air around the fiber, and it also might have been due to the random distribution of steel fibers in the samples which leads to a change in wave direction. In addition the samples with 80 l/d exhibited higher velocity than 60 l/d this could be attributed to the increase in density or length effect which decrease the time needed to pass the samples with 80 l/d. Commonly, adding hooked end steel fiber to the SCC disturbs the uniformity of the mixture leading to this result. Gencel et al. (2011) and Sanjeev (2020) obtained similar results, but AL-Ridha et al. (2020) claimed the opposite, saying the pulse velocity moved faster in the metal.

Table 11: Schmidt hummer test results and classification of different SCC mixes

Mix	**Rebound number of SCC**	**Class**
Control	38.53	Hard layer
60 l/d, 0.35%	38.23	Hard layer
60 l/d, 0.45%	37.30	Hard layer
60 l/d, 0.55%	35.97	Hard layer
80 l/d, 0.35%	38.13	Hard layer
80 l/d, 0.45%	39.67	Hard layer
80 l/d, 0.55%	38.30	Hard layer

Table 12: Ultrasonic pulse velocity test results and quality classification

Mix	Ultrasonic pulse velocity (km/second)	Class
Control	4.73	Excellent
60 l/d, 0.35%	4.61	Excellent
60 l/d, 0.45%	4.56	Excellent
60 l/d, 0.55%	4.52	Excellent
80 l/d, 0.35%	4.65	Excellent
80 l/d, 0.45%	4.62	Excellent
80 l/d, 0.55%	4.58	Excellent

4.4 Hardened Mix Properties

4.4.1 Compressive Strength

Table 13 and Figure 18 present the results of the different SCC mixes with various fiber V_f and l/d obtained from the σ_c test at 3, 7, and 28 days. The outcomes demonstrate that σ_c decreased as the fiber content increased in the case of 60 l/d (short fiber). This might have been due to the increase in the porosity of the concrete which causes a decrease in the strength of the SCC. Khaloo et al. (2015) found the same results, and Pilakoutas et al (2004) reported that inclusion of fiber in the mix caused the entrapment of more air voids around the fibers and inversely affected the σ_c.

On the other hand, the behavior with 80 l/d was different, the σ_c increased up to 0.45% volume fraction, then decreased with 0.55% fiber volume fraction. From these results it could be considered that 0.45% the optimum V_f with 80 l/d. This reduction beyond the optimum volume fraction can be attributed to the difficulties in scattering and distributing the steel fibers in the concrete, which negatively affects the homogeneity of the mix and leads to weakened concrete. Aghaee et al. (2015) observed the same phenomenon in their study.

Based on these results, it was obvious that σ_c was affected by the aspect ratio. Increasing the aspect ratio was accompanied by a decrease in the reduction in σ_c, this could be due to the effect of the fibers length which possibly was more influential in bridging the cracks developing within the material under the action of compressive forces as shown in flexural strength results and delaying the failure with improved resistance to compressive stresses. The lowest σ_c value was found with 60 l/d 0.55%, and the highest with 80 l/d 0.45% because of the reasons mentioned above. Generally, the σ_c of the SFR-SCC was lower than the control mix without fibers. Using SF as additive enhance the compressive strength by improving the filling capillary pores, distribute the load uniformly inside the concrete specimens and improve the physical properties which enhanced the compressive strength.

Table 13: Compressive strength test results of SFR-SCC

Mix Type	**3 days, MPa**	**7 days, MPa**	**28 days, MPa**
Control	42.0	52.1	69.2
60 l/d, 0.35%	35.3	45.4	62.1
60 l/d, 0.45%	34.7	41.2	55.1
60 l/d, 0.55%	30.5	38.1	52.5
80 l/d, 0.35%	37.6	48.9	62.6
80 l/d, 0.45%	39.8	51.3	64.8

80 l/d, 0.55%	38.7	50.1	63.0

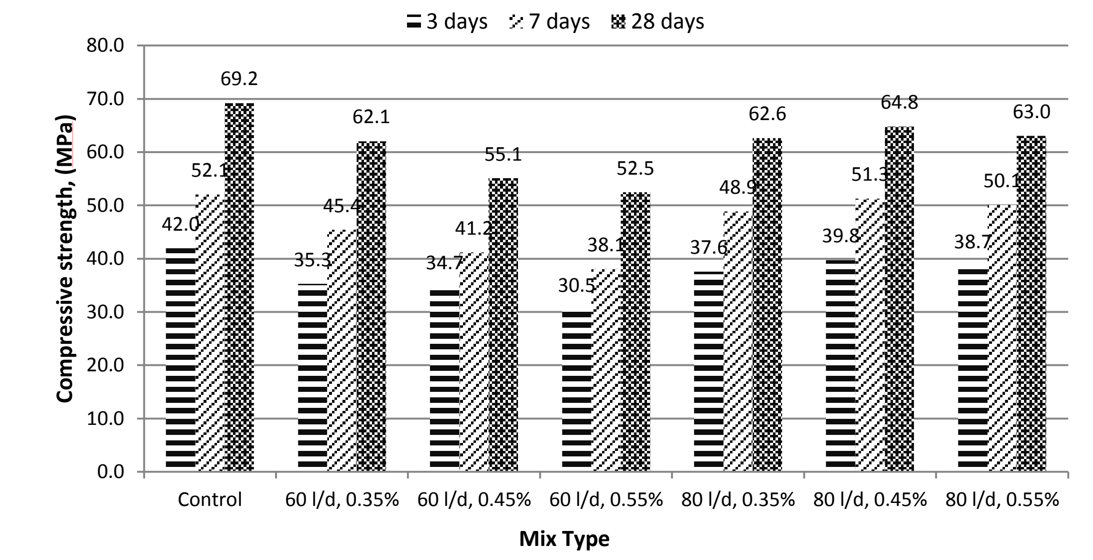

Figure 18:Effect of adding steel fibers on the compressive strength of SCC

4.4.2 Splitting Tensile Strength

Figure 19 shows that adding steel fibers with different aspect ratios to SCC increased the σ_s because of crack bridging behavior of hooked end steel fiber. The trend in Figure 20 shows that σ_s for both aspect ratios steadily increased as the fiber content increased in the mix. In addition, using silica fume as an additive enhanced the bonding properties between the materials inside the concrete matrix. The increase was 1.5%, 11.2%, and 16.0% with 60 l/d and 0.35%, 0.45%, and 0.55% volume fractions, respectively. For longer fibers with 80 l/d (50 mm length), the increase was 1.66%, 21.12%, and 41.26% with 0.35%, 0.45%, and 0.55% volume fractions, respectively. It was obvious that the longer fiber improved the tensile strength more than short fibers. Therefore, the tensile strength increased when the aspect ratio increased; that means the aspect ratio has a significant impact on the indirect tensile strength.

El-Dieb, (2009); Aslani et al., (2013); Iqbal et al., (2015); and Mastali et al., (2016) reported similar results, and they attributed that to some matrix properties such as length, shape, and mechanical behavior of the steel fiber.

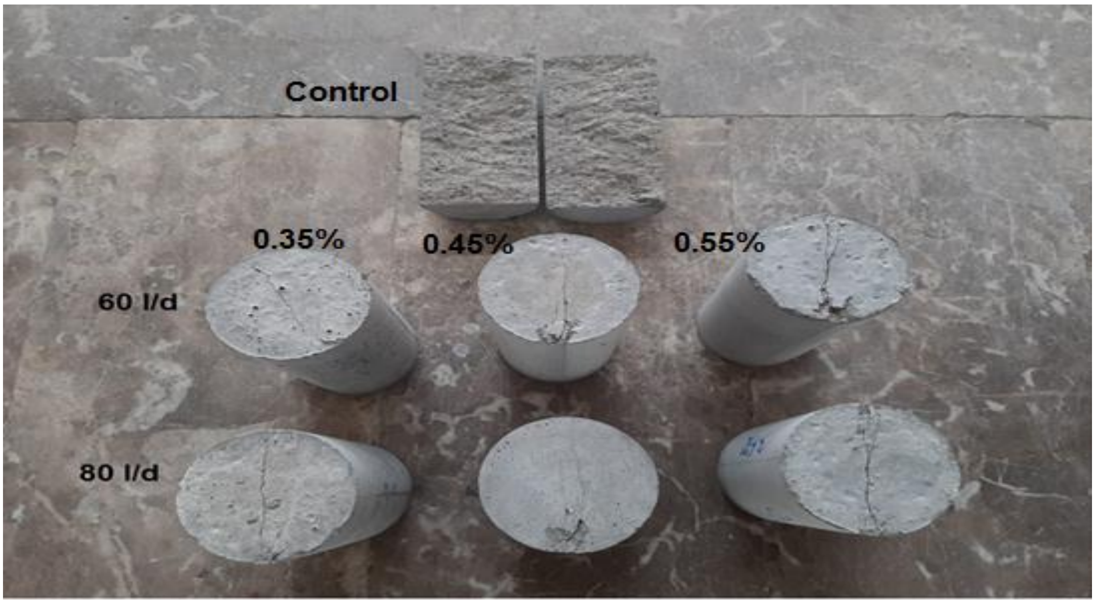

Figure 19: Effect of adding hooked end steel fiber on the splitting tensile strength of SCC

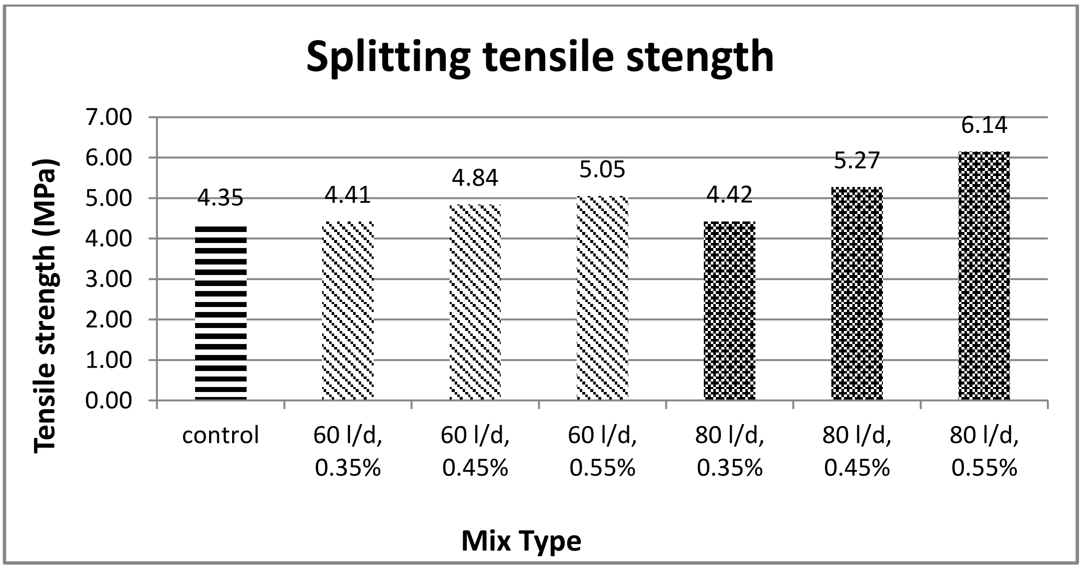

Figure 20: Splitting tensile strength test results of SFR-SCC

4.4.3 Flexural Strength Test

The influence of inclusion of hooked end steel fiber with different fiber volume fractions and aspect ratios are presented in Table 14 and Figure 21. Adding hooked end steel fiber to SCC caused a clear improvement in the behavior of the matrix, making it more ductile instead of brittle. In addition, adding the fibers eliminated sudden failure through crack bridging, and it also improved the post-crack resistance and energy absorption capacity (toughness) due to the end shape of the steel fibers and high tensile strength, as shown in Figure 22.

The outcomes indicate that σ_f of SCC gradually goes up when fiber volume fraction increases. Moreover, the aspect ratio has a crucial influence on the flexural strength. The long fibers (80 l/d) show higher flexural strength because they can hold more load (stress) compared to the short fibers (60l/d) which could be removed easily. Ponikiewski et al., (2013); Mastali et al., (2015); and Abbas (2013) revealed similar results. It was noticed that with 0.35% volume fraction, the increase was negligible for both aspect ratios, and this might be due to the weak interfacial zones that develops between the fibers and the matrix possibly is more influential than that of the crack bridging role of the fibers at 0.35% V_f. On the other hand, the highest improvement was with 0.55% of 80 l/d due to the reasons mentioned before.

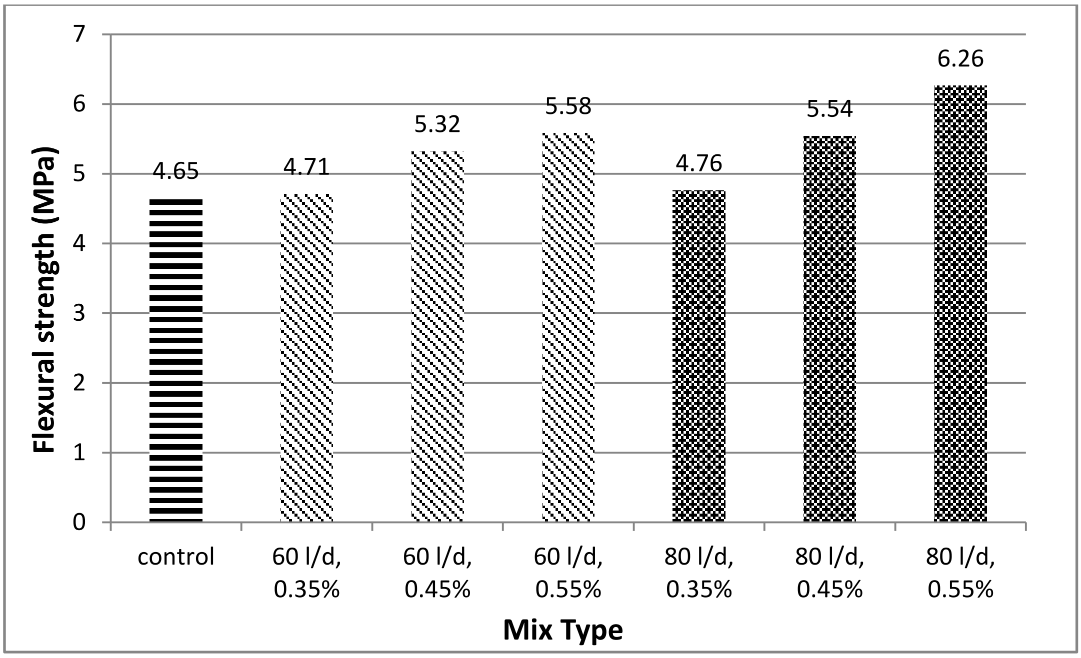

Figure 21: Flexural strength results of different SFR-SCC mixes

Table 14: Effect of adding different aspect ratios of hooked end steel fiber on SCC

Mix	Flexural strength (MPa)	Change%
control	4.65	_
60 l/d, 0.35%	4.71	1
60 l/d, 0.45%	5.32	14
60 l/d, 0.55%	5.58	20
80 l/d, 0.35%	4.76	2
80 l/d, 0.45%	5.54	19
80 l/d, 0.55%	6.26	35

Figure 22: Post-crack resistance

Flexural toughness results are shown in Figure 24. The curve was plotted using the data from the flexural machine (load–deflection) diagram presented in Figure 23. The data were analyzed using Excel and the area under force-deflection curve was calculated using OriginPro8 and taken to represent flexural toughness (see Figure 23). It is clear from the results that adding steel fiber improves the toughness of SCC and enhances energy absorption capacity after the first crack due to crack-bridging action. The control mix exhibited failure after reaching the peak load. Even SFR-SCC with 0.35% of fibers showed the same behavior for both long and short fibers at the low volume of fibers, which means this volume was not enough to absorb the energy after reaching the peak load. On the other hand, 0.45% and 0.55% fiber volumes of concrete developed flexural toughness. The effect of aspect ratio was obvious on the toughness as it increased as the aspect ratio increased. SFR-SCC with 3D hooked end fibers showed a softening behavior after the first crack in this experiment, and similar behavior was observed in the work of Ghanem and Obeid (2015).

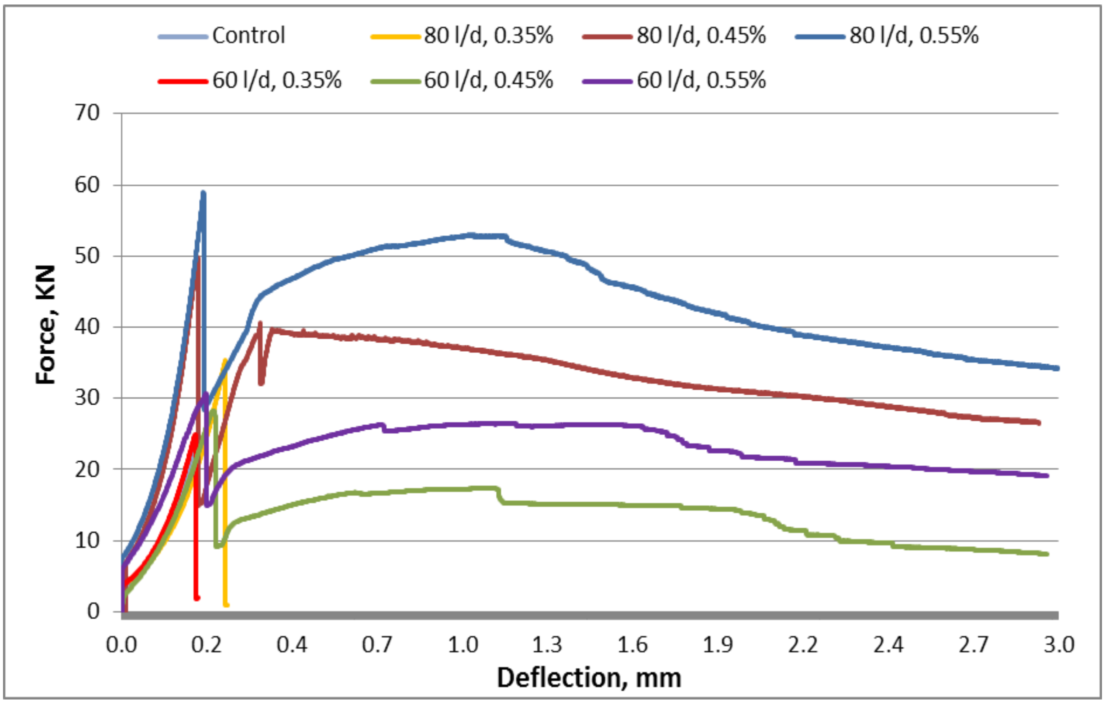

Figure 23: Load-deflection diagram of SFR-SCC

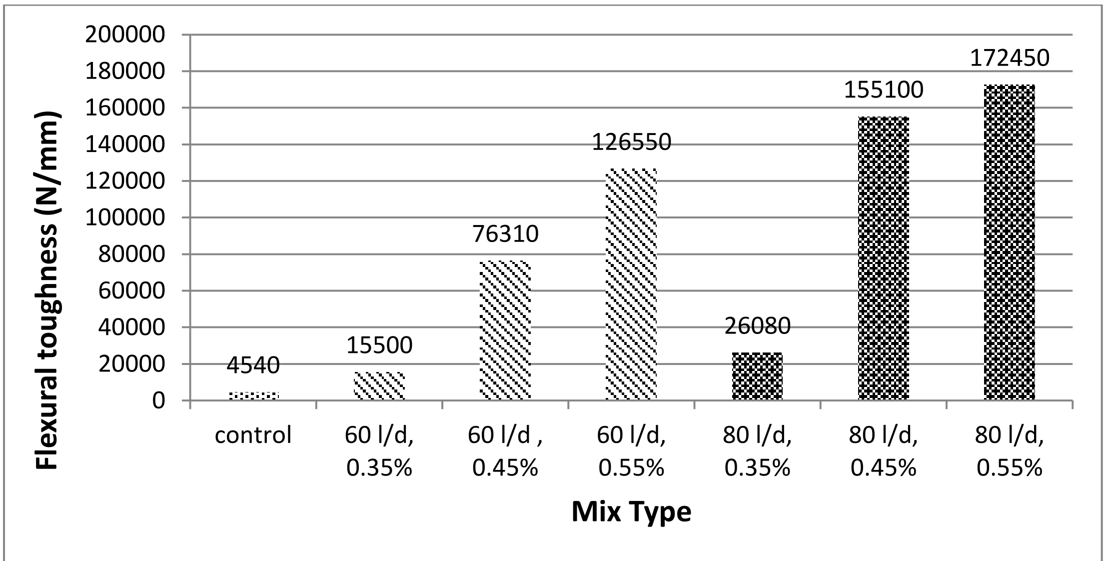

Figure 24: The effect of adding steel fibers on the flexural toughness of SCC

4.4.4 Impact Resistance Test

The average results for three cylindrical samples with dimensions of 150×63 mm obtained from the impact resistance test for the seven different mixes at 28 days are tabulated in Table 15 and presented in Figure 25.

Values obtained from the impact test illustrated that the improvement in the first visible crack is negligible when compared to plain SCC, and this might be attributed to the natural behavior of the concrete with low w/c ratio, or it could be due to the low V_f of StF. In contrast, the enhancement of post cracking behavior was pronounced, especially with long fiber. As the content of hooked end steel fibers increased, the number of required blows to ultimate crack failure increased for 60 and 80 l/d. The improvement was 9, 13, and 16 times for 0.35%, 0.45%, and 0.55% volumes of 60 l/d, and 15, 22, and 32 times for 0.35%, 0.45%, and 0.55% volumes of 80 l/d, respectively.

It is obvious that impact resistance increased with the increase in fiber content for 80 l/d and 60 l/d due to crack bridging action after the first crack appeared. In addition, the influence of the aspect ratio was clear where the highest increase was 0.55% of 80 l/d because of the length effect which is more difficult to pull out compared to short 60 l/d fiber.

Figure 26 shows the failure behavior of plain SCC and SFR-SCC. Plain SCC samples exhibited brittle failure and showed extremely low impact resistance due to the absence of fiber in the mix and low w/c ratio. In contrast, the failure in fibrous samples was ductile and distributed the dynamic load on the whole surface.

Table 15: Impact resistance test results

Mix	Number of blows		Impact energy (J)	N2 –N1	Increase in the ultimate crack %
	First crack (N1)	Ultimate crack (N2)			
Control	2	3	66.3	1	_
60 l/d, 0.35%	3	31	684.6	28	933
60 l/d, 0.45%	3	42	927.5	39	1300
60 l/d, 0.55%	4	52	1148.4	48	1633
80 l/d, 0.35%	3	49	1082.1	46	1533
80 l/d, 0.45%	3	74	1634.2	71	2367
80 l/d, 0.55%	4	106	2348.3	102	3433

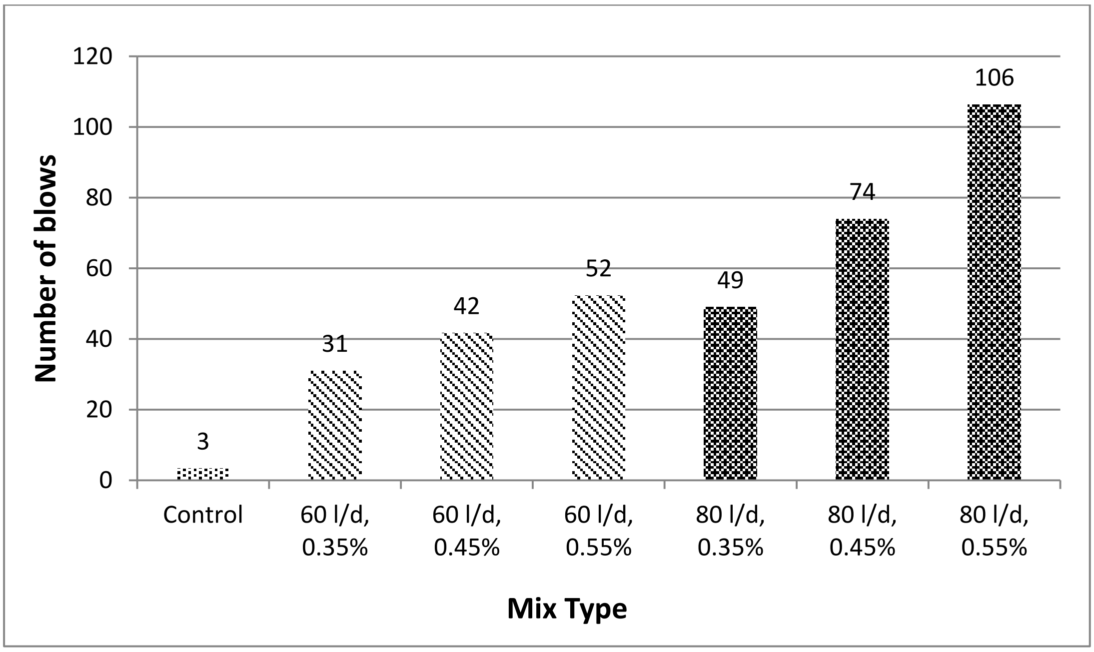

Figure 25: The effect of adding steel fibers on the number of blows

Figure 26: Behavior of SCC under impact load. (a) Without steel fiber (b) With 0.55%, 80l/d steel fibers

4.4.5 Permeability Test (Water Penetration)

The average of water penetration depth for the various specimens was measured in order to specify the durability of plain SCC and SFR-SCC, and to investigate the effect of inclusion of hooked end steel fiber on SCC at 28 days according to European Standard (EN 12390-8:2009).

Cubic samples were split after subjecting them to 500 kPa water pressure for 72 hours. The results of this test are in Table 16 and Figure 27 give a good indication regarding the durability of plain SCC, as the penetration was 17 mm for plain SCC. After evaluation of the readings, it was obvious that inclusion of steel fibers in SCC had a negative effect on permeability. The inclusion of fibers increased water penetration depth for the samples with 0.35%, 0.45%, and 0.55% of 60 and 80 aspect ratios with length of 30 mm and 50 mm by 6%, 29%, 59%, 0%, 24% and 47% relative to the control mix, respectively.

Although the results summarised in Table 16 shows that the inclusion of steel fibers greatly increases the water penetration depth of mortars, the increase in the aspect ratio of such fibers had a significant influence on reducing the water permeability of concrete. The previous results at higher aspect ratio of fibers 80l/d, already demonstrated a higher compressive strength attainment, which is largely attributed to the denser microstructural development accomplished in the porous media. This performance perhaps is mainly responsible from the systematic reduction of the water penetration depth of concrete prepared with higher aspect ratio of steel fibers. Zhang et al. (2019) reported the same results. On the other hand, Huang and Xie (2011) observed that adding steel fibers in hydraulic concrete reduced permeability and enhanced performance of the concrete due to crack bridging behavior.

In general, the different mixes had good durability due to high compatibility, good homogeneity, well-graded aggregates, and inclusion of the silica fume which fills the small pores inside the matrix. Santos et al., (2019); and Kapoor et al., (2016) pointed out in their studies that using minerals such as SF and fly ash can enhance the durability of concrete.

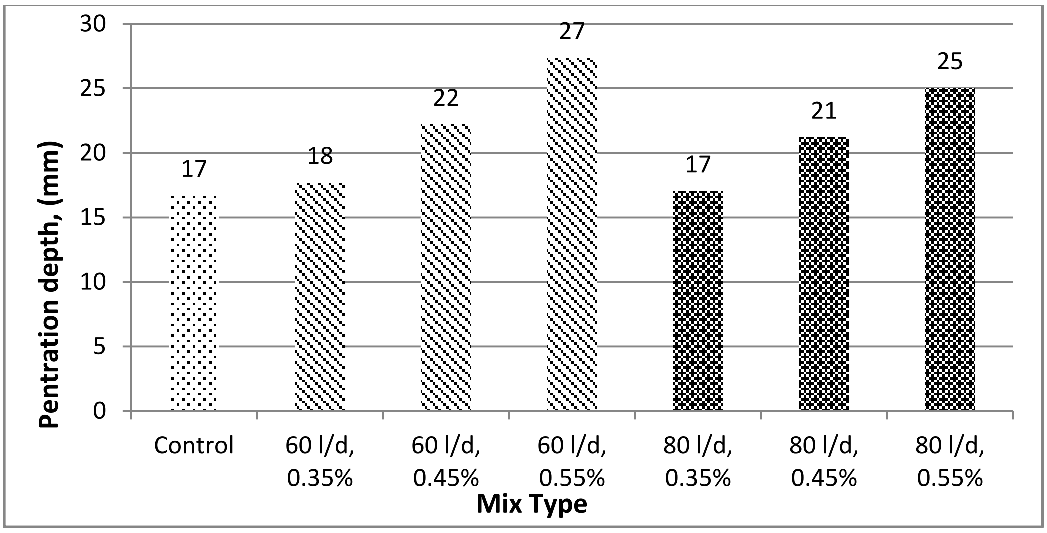

Figure 27: Effect of adding steel fiber on the permeability of SCC

Table 16: Permeability test results of various SRF-SCC

Mix	Water penetration depth (mm)	Increase %
Control	17	_
60 l/d, 0.35%	18	6
60 l/d, 0.45%	22	29
60 l/d, 0.55%	27	59
80 l/d, 0.35%	17	0
80 l/d, 0.45%	21	24
80 l/d, 0.55%	25	47

Figure 28: Effect of adding steel fiber on water pentration depth of SCC. (a) 0.35%, (b) 0.45%, (c) 0.55% volume fractions

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this study, seven different mixes of SCC were prepared with constant w/b ratio and with superplasticizer and silica fume as additive. One control mix had no steel fiber and the other six mixes had steel fibers with the following specifications: Two series with two different aspect ratios of 60 and 80, three different volume fractions (0.35%, 0.45%, and 0.55%) of hooked end steel fiber were selected for testing. The results obtained after testing fresh and hardened SCC led to the following conclusions and suggestions for other researchers. These are presented below:

1. All the required SCC criteria of fresh properties can be meet with SFR-SCC regarding to flowability, filling ability and passing ability, even though adding steel fiber to SCC negatively affects the workability.
2. The highest compressive strength of SFR-SCC can be achieve with 80 l/d, 0.45%.
3. Adding hooked end steel fiber enhanced σ_f and σ_s of SCC due to crack bridging action, post-crack behavior, and the end shape of the fibers which increased bonding between the fibers and the concrete matrix. In addition, the split tensile and flexural strengths of the SFR-SCC increased as the l/d and V_f increased.
4. According to the results, toughness was the property most highly influenced by adding hooked end steel fiber depending on the l/d and the V_f of the fibers.

The highest enhancement was with 80 l/d of 0.55% V_f, as the longer fibers held the cracks for a longer time and absorbed more energy.

5. The results show that inclusion of steel fiber in SCC increases IR and enhances ductility of the SCC by distributing the load over the concrete samples compared to the control mix. Moreover, the length of the fiber was one of the main factors leading to an increase in impact resistance.
6. Overall, the quality of the various mixes of SCC was excellent due to the high compatibility of the SCC, including the mixes with steel fiber, since the pulse velocity for all the mixes was higher than 4.5 km/S. This was clear for the different SCC mixes because they had good durability, and the penetration depth did not exceed 27 mm. Yet, the SFR-SCC mixes provided higher permeability compared to the control mix.
7. Using Silica fume as an additive influenced the fresh properties by improving the consistency of the mix. In general, silica fume had a good impact on the hardened properties. This effect is achieved through increasing the compressive strength, enhancing the tensile strength by increasing the bonds between the particles inside the mix, and improving the quality of the mixture by filling the voids due to the high fineness.

5.2 Recommendations for Future Studies

1. Investigation of the effect of adding hooked end steel fiber on the creep and shrinkage behavior of SCC.
2. Studying the effect of sulfate solution on the samples to determine the mass loss and corrosion appearance inside.
3. Studying the effect of adding hybrid fibers (micro–macro) on the mechanical properties.

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