

**REPUBLIC OF TURKEY
GAZİANTEP UNIVERSITY
GRADUATE SCHOOL OF
NATURAL & APPLIED SCIENCES**

**EFFECT OF NANO SILICA AND STEEL FIBER ON FRESH
STATE AND MECHANICAL PROPERTIES OF SELF-
COMPACTING GEOPOLYMER CONCRETE**

**M.Sc. THESIS
IN
CIVIL ENGINEERING**

**BY
AYAD ALI RASHEED
JANUARY 2019**

JANUARY 2019

M.Sc. in Civil Engineering

AYAD ALI RASHEED

**Effect of Nano Silica and Steel Fiber on Fresh state and Mechanical
Properties of Self-Compacting Geopolymer Concrete**

**M.Sc. Thesis
In
Civil Engineering
Gaziantep University**

Supervisor

Assist. Prof. Dr. Mehmet Eren Gülşan

by

Ayad Ali RASHEED

January 2019



© 2019 [Ayad Ali RASHEED]

REPUBLIC OF TURKEY
UNIVERSITY OF GAZİANTEP
GRADUATE SCHOOL OF NATURAL & APPLIED SCIENCES
CIVIL ENGINEERING DEPARTMENT

Name of the thesis: Effect of Nano Silica and Steel Fiber on Fresh State Mechanical Properties of Self-Compacting Geopolymer Concrete

Name of the student: Ayad Ali RASHEED

Exam date: 21.01.2019

Approval of the Graduate School of Natural and Applied Sciences

Prof. Dr. A. Necmeddin YAZICI
Director

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

Prof. Dr. Hanifi ÇANAKCI
Head of Department

This is to certify that we have read this thesis and that in our consensus opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science

Assist. Prof. Dr. Mehmet Eren GÜLŞAN
Supervisor

Examining Committee Members:

Signature

Prof. Dr. Abdulkadir ÇEVİK

.....

Assist. Prof. Dr. Mehmet Eren GÜLŞAN

.....

Assist. Prof. Dr. Hüseyin Çağan KILINÇ

.....

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Ayad Ali RASHEED

ABSTRACT

EFFECT OF NANO SILICA AND STEEL FIBER ON FRESH STATE MECHANICAL PROPERTIES OF SELF-COMPACTING GEOPOLYMER CONCRETE

RASHEED, Ayad Ali

M.Sc. Thesis in Civil Engineering

Supervisor: Assist. Prof. Dr. Mehmet Eren Gülşan

January 2019

68 pages

This thesis investigates the properties of the self-compacting geopolymer concrete (SCGC) in both the fresh and hardened state under the combined addition of nano-silica (NS) and steel fiber (SF). Nine mixtures of SCGC containing different percentages of NS (0 %, 1 % and 2 %), and different percentages of SF (0 %, 0.5 % and 1 %) were prepared for the study. SCGC were prepared using 50 % fly ash (FA) and 50% ground granulated blast furnace slag (GGBFS) with a constant alkaline activator to binder ratio of 0.5. A blend of sodium silicate solution (Na_2SiO_3) and sodium hydroxide solution (NaOH) with a ratio of 2.5 has been chosen as an alkaline activator. The Fresh state and hardened concrete tests including slump, flowability, workability, compressive strength, bonding strength, and flexural strength were carried out in the study. Experimental results were examined in detail to determine the impact of important factors on mechanical performance of SCGC. Furthermore, correlations between the experimental data were evaluated to explore the relationships between the fresh and hardened state properties of geopolymer concretes. Experimental results showed that the combined use of NS and SF affected the fresh state properties adversely, while it improved the bond strength and flexural performance of the SCGC specimens significantly. In addition, the effect of NS was predominant regarding fresh state properties and compressive strength, while the effect of SF was superior regarding flexural and bonding strength.

Keywords: Self-compacting geopolymer concrete (SCGC); fresh state properties; nano-silica; steel fiber; bonding strength; and flexural toughness.

ÖZET

NANO SİLİKA VE ÇELİK LİFİN KENDİLİĞİNDEN YERLEŞEN GEOPOLİMER BETONUN TAZE HAL VE MEKANİK ÖZELLİKLERİ ÜZERİNDEKİ ETKİSİ

RASHEED, Ayad Ali

Yüksek Lisans Tezi, İnşaat Mühendisliği

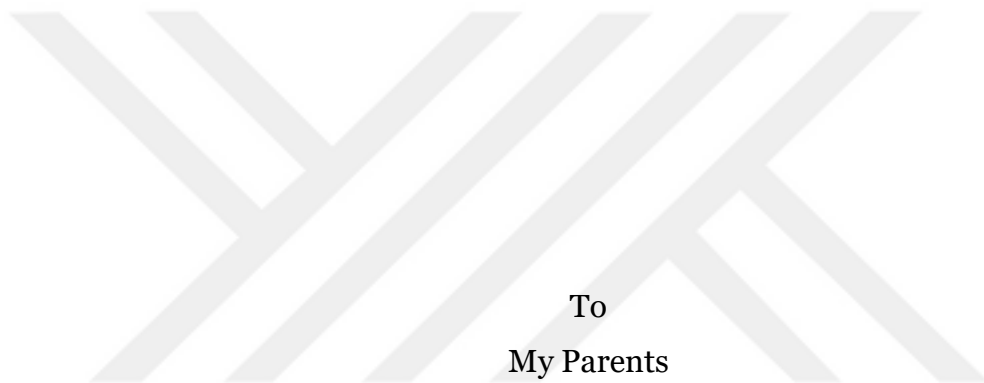
Tez Danışmanı: Dr. Öğr. Üyesi Mehmet Eren GÜLŞAN

Ocak 2019

68 sayfa

Bu tez kendiliğinden yerleşen geopolimer betonun nano silika ve çelik telin bir arada eklenmesi altında hem taze, hem de mekanik özelliklerini araştırmaktadır. Çalışma için farklı oranlarda nano silika (% 0, % 1 ve % 2) ve çelik lif (% 0, % 0.5 ve % 1) muhteva eden 9 adet kendiliğinden yerleşen geopolimer beton karışımı hazırlanmıştır. Kendiliğinden yerleşen geopolimer beton sabit 0.5 alkalin aktivatör / bağlayıcı oranı ile % 50 uçucu kül ve % 50 öğütülmüş granül yüksek fırın cürufu kullanılarak hazırlanmıştır. 2.5 oranında sodyum silikat (Na_2SiO_3) ve sodyum hidroksit (NaOH) çözeltileri karışımı alkali aktivatör olarak seçilmiştir. Çalışmada, çökme, akıcılık, işlenebilirlik, basınç mukavemeti, aderans dayanımı ve eğilme mukavemetini kapsayan taze ve sertleşmiş beton testleri yapılmıştır. Önemli faktörlerin geopolimer betonun mekanik performansı üzerindeki etkisini belirlemek için deney sonuçları detaylı bir şekilde incelenmiştir. Ayrıca, geopolimer betonların taze ve sertleşmiş durumdaki özellikleri arasındaki ilişkiyi araştırmak için deneysel sonuçlar arasındaki uyumluluk değerlendirilmiştir. Deneysel sonuçlar nano silika ve çelik lifin birlikte kullanımının taze durum özelliklerini olumsuz yönde etkilediğini; ancak kendiliğinden yerleşen geopolimer betonun aderans dayanımını ve eğilme performansını önemli derecede iyileştirdiğini göstermiştir. Ayrıca, nano silikanın etkisi taze durum özellikleri ve basınç mukavemeti açısından daha baskın iken; çelik lifin etkisi eğilme ve aderans dayanımı açısından daha etkindir.

Anahtar Kelimeler: Kendiliğinden yerleşen geopolimer beton; taze durum özellikleri; nano silika; çelik tel; aderans dayanımı ve eğilme tokluğu.



To
My Parents
And

All the members of my family

ACKNOWLEDGEMENT

I would like to express my sincere gratitude and appreciation to my supervisor **Assist. Prof. Dr. Mehmet Eren GÜLŞAN**, for his invaluable guidance, useful advice, and continuous support he has provided me during the preparation of this thesis. I am happy and proud to work under the supervision of a gentleman, knowledgeable and professional supervisor like him.

Special greetings and thanks to my parents, all members of my family for their continued support and encouragement during the years of study.

I would also like to extend my gratitude and thanks to all my friends and all who helped me during the laboratory work, testing and writing the thesis.

TABLE OF CONTENTS

	Page
ABSTRACT	vi
ÖZET	vii
ACKNOWLEDGEMENT	viii
TABLE OF CONTENTS	ix
LIST OF FIGURES	xii
LIST OF TABLES	xiv
LIST OF SYMBOLS/ABBREVIATIONS	xv
CHAPTER 1	1
INTRODUCTION	1
1.1 General	1
1.2 Research significance	4
1.3 Outline of the thesis.....	5
CHAPTER 2	6
LITERATURE REVIEW	6
2.1 Nano-silica	6
2.2 Steel fiber	7
2.3 Fresh state properties of geopolymer concrete.....	9
2.4 Mechanical properties of geopolymer concrete	11
2.4.1 Compressive strength	11
2.4.2 Bond strength	12
2.4.3 Fracture property	12

2.5	Effect of NS on mechanical properties of SCGC	13
2.5.1	Effect of NS on compressive strength of SCGC	14
2.5.2	Effect of NS on bond strength of SCGC	13
2.6	Effect of SF on mechanical properties of SCGC	16
2.6.1	Effect of SF on compressive strength of SCGC.....	16
2.6.2	Effect of SF on fracture property of SCGC.....	18
2.7	The combined effect of NS and SF on properties of SCGC	19
CHAPTER 3		21
EXPERIMENTAL PROGRAM		21
3.1	Materials.....	21
3.1.1	Fly ash and slag.....	21
3.1.2	Nano-silica (NS).....	22
3.1.3	Steel fiber (SF)	23
3.1.4	Aggregates.....	24
3.1.5	Superplasticizer	24
3.1.6	Alkaline solution	25
3.2	Concrete mix design and mixing procedure.....	26
3.3	Fresh state tests.....	28
3.4	Curing of the SCGC specimens	31
3.5	Hardened state tests	31
CHAPTER 4		36
EXPERIMENTAL RESULTS AND DISCUSSIONS		36
4.1	Fresh state properties.....	36
4.1.1	Effect of NS and SF on slump flow diameter	37
4.1.2	Effect of NS and SF on the slump flow time	37
4.1.3	Effect of NS and SF on V-funnel flow time.....	38

4.1.4	Effect of NS and SF on L-box height.....	40
4.2	Hardened state properties of SCGC	42
4.2.1	Compressive strength	42
4.2.2	Bond strength	42
4.2.3	Flexural strength.....	44
4.3	Fracture performance	46
4.4	Correlation between fresh and hardened properties of SCGC	49
CHAPTER 5		54
CONCLUSIONS		54
5.1	Conclusions of the study	54
5.2	Recommendations for Future Research	55
REFERENCES		56

LIST OF FIGURES

	Page
Figure 3.1 Photographic view of (a) FA (b) GGBFS	21
Figure 3.2 Nano-silica used in SCGC	22
Figure 3.3 Hooked-end steel fiber used in SCGC	23
Figure 3.4 (a) coarse aggregate (b) fine aggregate	24
Figure 3.5 Superplasticizer	24
Figure 3.6 (a) and (b) sodium silicate, (c) and (d) sodium hydroxide pellets	25
Figure 3.7 The procedure of preparing alkaline activator and GPC	26
Figure 3.8 The moulds used and casting of hardened state specimens	27
Figure 3.9 Slump flow tools and testing	28
Figure 3.10 V-funnel details and testing	29
Figure 3.11 L-Box details and testing	29
Figure 3.12 The furnace used to curing of SCGC specimens	31
Figure 3.13 A specimen under compressive strength machine	32
Figure 3.14 Dimensions of the pullout test specimen	32
Figure 3.15 (a) pullout test set-up (b) SCGC specimen under the pullout	33
Figure 3.16 (a) Test set-up and details of specimen (b) specimen under TPB test ..	35
Figure 4.1 Slump flow diameter of SCGC	36

Figure 4.2	Effect of NS and SF on the slump flow diameter	37
Figure 4.3	Slump flow duration versus NS and SF relationship	38
Figure 4.4	The combined effect of NS and SF on V-funnel	39
Figure 4.5	The relationship between V-funnel and T_{500} flow time	40
Figure 4.6	The variation of L-Box height ratio with NS level and SF	41
Figure 4.7	Influence of NS and SF on compressive strength	42
Figure 4.8	The together influence of NS and SF on bond strength	43
Figure 4.9	Typical failure patterns of SCGC	44
Figure 4.10	Effect of NS and SF on the load-displacement curve of SCGC	45
Figure 4.11	Influence of NS and SF on the flexural strength	46
Figure 4.12	Effect of NS and SF on Fracture Energy of SCGC	47
Figure 4.13	Effect of NS and SF on the stress intensity factor	47
Figure 4.14	Correlation between the fresh properties of SCGC	50
Figure 4.15	Correlation between the fresh and hardened properties of SCGC	51
Figure 4.16	Correlation between the hardened properties of SCGC	53

LIST OF TABLES

	Page
Table 2.1 The limits of fresh state tests of concrete as per EFNARC (2002)	10
Table 3.1 Physical properties and chemical compounds of FA, GGBFS, and NS ..	22
Table 3.2 Properties of the used SF	23
Table 3.3 Mixture proportions of self-compacting geopolymer concrete	30
Table 4.1 Slump flow, viscosity, and PA classes as per EFNARC specifications...	40
Table 4.2 The results of Fresh and hardened tests.....	48

LIST OF SYMBOLS/ABBREVIATIONS

OPC	Ordinary Portland cement
CO ₂	Carbon dioxide
GPC	Geopolymer concrete
FA	Fly ash
GGBFS	Ground granulated blast furnace slag
NaOH	Sodium hydroxide
Na ₂ SiO ₃	Sodium silicate
SCGC	Self-compacting geopolymer concrete
SP	Superplasticizer
C-S-H	Calcium-silica-hydrated
NS	Nano-silica
SF	Steel fiber
SSA	Specific surface area
SiO ₂	Silica dioxide
HESF	Hooked-end steel fiber
ACI	American concrete institute
l/d	Aspect ratio of steel fiber
V _f	Volume fraction of steel fiber
EFNARC	European federation of national associations representing for concrete
RILEM	International union of laboratories and experts in construction materials
ASTM	American system for testing materials

SCC	Self-compacting concrete
W/C	Water/cement ratio
TPB	Three-point bending
PA	Passing ability



CHAPTER 1

INTRODUCTION

1.1 General

Concrete is a preferred construction material and widely used in the world. For five decades, Massive amounts of concrete have been used extensively for construction purposes. It is being dramatically used day by day because of its versatility, high strength, moldability, and numerous other characteristics, thus the utilization of traditional concrete has expanded. Ordinary Portland cement (OPC) has mainly adopted as a binder for concrete. The manufacture of cement requires a very high temperature which means using large amounts of energy. It has found that the manufacture of each ton of OPC releases almost 1 ton of carbon dioxide (CO₂) (Hasanbeigi et al., 2010). Portland cement production contributes 5-7 % of entire universal CO₂ releases (Chen et al., 2010). The production of OPC needs to consumption of huge amounts of energy on the deterioration of limestone, Burning of fuel, and putrefaction of limestone resulting in extensive releases of CO₂. Analysis on the emissions has shown a frightening ratio between the manufacture of cement and CO₂ emissions (54% through calcination and 46% through the burning of fuels) (Gunasekara et al., 2015). It is stated that the worldwide manufacture of Portland cement provides about 1.35 billion tons greenhouse gas releases yearly (Malhotra, 2002; Hardjito et al., 2004). Due to that, the CO₂ release has been stated to be up to 13,500 million tons, which is the sum of 7% of greenhouse gases yearly universal (Naskar and Chakraborty, 2016). The predictions identified that the annual global manufacturer of PC would growth to 4.38 billion tons in 2050 founded on 5% increase per year (Schneider et al., 2011). It additionally consumes a huge quantity of rock that may lead to diminishing in any day (Nuruddin et al., 2010). For many years ago the utilization of cement as a binder in concrete has been criticized by many specialists in the protection of the environment from pollution.

This criticism comes from the damage caused by the cement industry to the environment through the emission of CO₂ which cause high temperatures and thus the occurrence of global warming as well as to reduce the consumption of natural resources (Reddy and Kumar, 2017). CO₂ emissions are also likely to increase by up to 50% from present levels in 2020 (Naik, 2005). In order to reduce the use of cement in concrete, many studies have been conducted to find a suitable alternative to OPC to reduce its impact on the environment; As a result, a kind of binder was formed from an aluminosilicate activated in a high alkaline solution, this binder is known as geopolymer cement (Nuruddin et al., 2011). This cementitious possesses an environmental advantage as it can decrease the CO₂ release to the atmosphere by about 80% compared to OPC (Castel and Foster, 2015).

Geopolymer concrete (GPC) is a novel combination that does not require the existence of OPC as a binder. Henceforth, in place of Portland cement, some of supplementary cementitious materials are used such as fly ash (FA), ground granulated blast furnace slag (GGBFS), metakaolin and silica fume, etc. These materials contain large amounts of silicon and aluminum is activated with chemical compounds such as sodium hydroxide (NaOH) and sodium silicate (Na₂SiO₃) alkaline liquids to form the geopolymer binder (Reddy and Kumar, 2017).

Davidovets discovered the geopolymer concrete by his proposing in 1978, where he stated that the binders might be formed through the polymer interaction with an alkaline liquid of both silicon and aluminum in by-product materials like fly ash. He has described this binder as geopolymers. Geopolymers have appeared as new materials in the engineering field and are likely to play a significant role in the production of eco-friendly construction materials. It has a very slight greenhouse influence when compared to normal concrete, since, it uses waste a lot, and they are also economical (Duxson et al., 2007; Raijiwala and Patil, 2011).

Generally, the geopolymer has very good mechanical properties as it acquires high early strength and has good resistance to acids and sulfates. In addition, it has low creep and shrinkage (Davidovits, 1994; Wallah and Rangan, 2006). The manufacture of raw materials for the geopolymer needs less energy than ordinary concrete. Since, it is found that the geopolymer releases CO₂ less than the OPC by 5-6 times. This is because of the low calcification temperature in the geopolymer (Davidovits, 1993;

Davidovits, 2008). CO₂ which is emitted from the fuel needed to produce one ton of geopolymer cement is about 0.18, which is less than CO₂ emitted from Portland cement production about 1 ton (Davidovits, 2002; Davidovits, 2015). The utilize of GPC is not limited to its contribution to reducing the emissions of CO₂ only, but also to the consumption of industrial waste and by-products, thus contributing to the transformation of harmful material into useful building materials (Hardjito et al., 2004).

On the other hand, acid resistance is a worthwhile feature in structures of concrete which utilize in harsh environments (Taylor, 1994; Scrivener and Young, 2014). Therefore, geopolymers based on aluminasilicate instead of calcium-silicate-hydrate (C-S-H) bonds for structural safety (Bouguermouh et al., 2017). In some countries, the geopolymer concrete is used as structure members (Škvára et al., 2005).

Self-compacting geopolymer concrete (SCGC) is a novel idea and one of the latest developments in the concrete technology which does not need vibration for putting and placing (Reddy and Kumar, 2017).

Superplasticizers are used to increase the workability of concrete thus, improvement casting operation, easy placement in congested reinforcing bars, improvement the unification around the reinforcement and bonding with the reinforcement, and a faster rate of casting, Thus reducing the total cost (Okamura and Ouchi, 2003; F.E.F.P. Group, 2005).

It is considered that the high volume paste in self-compacting concrete (SCC) mixtures assist to diminish the contact between the fine aggregate particles and improve the workability. The main functions of superplasticizer (SP) in SCGC are to acquire adsorbed on to binder grains, move a negative charge to them which repulse each other and acquire deflocculated and scattered mixture (F.E.F.P. Group, 2005). This provides perfect workability and better performance by enhancing the fresh and hardened properties thus improve the microstructure of SCGC and get better compressive strength (Nuruddin et al., 2010). Lately, nano technology has been presented in the applications of civil engineering. One of the most used nanomaterials is nano-silica (NS). It possesses a pozzolanic tincture and has the capacity to cooperate with the free lime and composes an extra C-S-H gel which gives durability, strength, and impermeability to concrete (Ibrahim, 2017). Because of the large specific surface area (SSA), the stick of the NS concrete is greater than

the normal concrete; also it has a better permeability resistance (Ji, 2005). According to the literatures that found on cement or concrete it was showed that adding of NS even in a few amounts improves the mechanical properties of cementitious materials (Shih et al., 2005).

Steel fiber is another mixing material that has been used to develop the mechanical properties of concrete during the last decades. The rupture of the concrete largely depends on the composition of the crack because of the loading influences. Changes in temperature and dampness lead to microscopic cracks in the mortar that are located on the surface of the coarse aggregate. Also, the nonstop loading causes the cracks to spread over the concrete body (Tavakoli et al., 2006). Hence, using of SF in concrete improves some of the mechanical properties such as fracture toughness, flexural strength, impact, thermal shock, and resistance to fatigue. The adding of SF to concrete at different rates gives great results in compressive strength, splitting tensile strength, and modulus of rupture of high strength concrete (Song and Hwang, 2004).

The researches of together influences of NS and SF on the fresh and hardened properties of self-compacting geopolymer concrete are few and scarce. This led us to study and investigate the effect of both materials on eco-friendly alkali activated low calcium FA and GGBFS blends in both fresh and hardened states in order to determine the optimum quantity of each material in the self-compacting geopolymer concrete.

1.2 Research significance

The main aim of this research is to determine and investigate the combined effect of NS and SF when added in varying proportions to the FA/GGBFS based-SCGC on fresh state and mechanical properties of SCGC. All the specimens are compared with each other as well as with the control specimens to present the difference and find out the most appropriate ratios of these parameters in this unique type of concrete. This research contributes the support efforts to reduce the utilizing of cement as a binding material and thus diminish the liberation of CO₂ in the ambiance as well as contributing to the use of useless industrial by-products and converting them into useful materials, thus, production an eco- friendly concrete.

1.3 Outline of the thesis

This thesis is ordered into five chapters to achieve the thesis objectives.

Chapter 1: describes the damages of ordinary Portland cement production, introduction to SCGC, the targets, and the organization of the research.

Chapter 2: in this chapter a simplified explanation of nano-silica and steel fiber is presented and its effects on geopolymer concrete in general as per previous research.

Chapter 3: describes the materials, casting procedures, and different types of tests performed for self-compacting geopolymer concrete.

Chapter 4: In this chapter, the experimental results of the tests have been explained and discussed.

Chapter 5: This chapter presents the main results achieved by this research.

CHAPTER 2

LITERATURE REVIEW

2.1 Nano-silica

In 2004, the first industrial-scale use of nano-silica in cementitious composites was recognized. Brian Green who is a member of the US Army Corps of Engineers was a pioneer regarding use of nano-silica in order to build up a rock-matching grout for military applications. His work emerged out of issues relating with segregation of grouts included of heavyweight aggregates, especially hematite. The nano-silica was added to the heavyweight grout mixture as a viscosity-modifying agent. It increased the thickness of the grout mixture, guaranteeing the steady and universal suspension of the hematite aggregate while the grout was in a plastic state. The viscosity-modifying agent used was in the form of an ultra-fine shapeless colloidal silica or nano-silica with a particle distribution ranging between 3 and 100 nm. Green discovered that the nano-silica not just upgraded the suspension of hematite and prevention of segregation but also improved the density and strength of the grout (Green, 2008).

It has been shown that the performance of NS regarding development of early strength comes from the large specific surface area (SSA) of free silica (Said and Zeidan, 2009). Similar to class F fly ash, the free silica provided by the NS combines with calcium hydroxide in the hydrating cementitious matrix to produce more C-S-H. Because of the smaller size of the NS particles, there is a greater total SSA of free silica which is available for faster pozzolanic reaction leading to increase in the strength at early ages and durability of concrete (Nazari and Riahi, 2011). In spite of the ever-growing of the popularity of NS in concrete and composites of cement, a profound concept of the impact of NS is required in both the academic and construction fields to provide the industry confidence in this unique technology.

At the present nano technology was presented in the applications of civil engineering. It is one of the most promising fields of science. From this point on, specialists in the field of concrete are studying NS as a new admixture. It has a very high ratio of amorphous silica, very large SSA, and tiny dimensions (Fallah and Nematzadeh, 2017).

Nano-silica is a silica dioxide (SiO_2) nano-particle non-natural manufactured of porous and strictly aspheric particles with great possible advantages. The size of nano-particles is extremely small and about one per thousand of the cement particles size (Silica-Fume Association, 2005). It is a crystal composition produced in detail as sand, quartz, and numerous other minerals. According to nano-silica composition particles are distributed by two levels in particles: S-type nano- SiO_2 (spherical particles) and P-type nano- SiO_2 (porous particles). P-type nano- SiO_2 possess much greater surface area compared with the other type of nano- SiO_2 (US Research nano-materials, 2015) P-type nano- SiO_2 has a number of nano-porous with the pore rate of 0.611 ml/g. The size of NS particles ranges from 15 to 20 nm. NS is one of the best nominees to be utilized as an alternative material to Portland cement. It is well known that utilizing mineral replacement like nano-silica will develop the durability and strength of concrete, due to the high dense fine particles, the larger surface area, and the high SiO_2 content. nano-silica is more selected than silica-fume because the size of NS particle is smaller than the size of silica-fume with a larger surface area. The fineness of NS particles affects the cement paste or mortar properties, where, the pore size increases with increasing the fineness; this will result in increasing the pozzolanic reaction.

2.2 Steel fiber

The geopolymer concrete has many benefits such as high mechanical properties, high resistance to fire, and low creep and shrinkage as compared with OPC, but it is brittle and has low tensile and flexural strength (Farhan et al., 2018). Researchers explored adding of different kinds of fibers such as steel fiber in GPC to decrease its brittleness by the development of tensile and flexural strengths, energy absorption capabilities, and fracture toughness of GPC (Farhan et al., 2018, August). Also, SF improves the load capacity, curbs the crack growth rate and width of the cracks; this is due to adding of SF in GPC, resulting in higher friction and higher clamping

pressure (Shaikh, 2013; Ranjbar et al., 2016). The addition of SF increases the symmetry and homogeneity of concrete which increases its ductility. When the SF used in the concrete is randomly distributed, they curb the cracking mechanism and restrict the spread of the cracks, thus increasing ductility and strength of concrete (Wafa and Ashour 1992). For structural applications, SF should be utilized mostly as an auxiliary reinforcement (ACI Committee, 1988). The usage of the hooked-end steel fiber (HESF) and crimped round steel fiber with dissimilar rates in the same concrete mix have affected the compressive and splitting tensile strengths (Vairagade and Kene, 2013). The effectiveness of the SF in GPC depends on many factors comprising the volume fraction (V_f), SF geometry, aspect ratio (l/d), and tensile strength of SF (Aydın, 2013).

In general, l/d of steel fiber utilized in concrete varies from 50 to 100 (Yazıcı et al., 2007). Likelihood of varied distribution of fibers in the concrete mix increases by increasing l/d . Moreover, volume fraction strikingly influences the workability of concrete. The best V_f values in mixtures of concrete are 0.5% to 2.5% by volume of concrete (Bentur and Mindness, 1990; Gambhir, 1986). When the ratio of steel fiber in concrete exceeds 2%, it can improve ductility, as well as enhance the fracture toughness, strain hardening, and some other mechanical properties of the concrete (Li, 1998). There are many shapes of SF available including hooked, straight, crimped, twisted, single and collated (Soufeiani et al., 2016). The disadvantages of steel fiber are that it reduces the workability and accelerated stiffening of concrete. Thus, increasing the construction labors and time because this requires more vibration to make the concrete workable. As well as increasing the dead load (Li, 2011). Steel fiber reinforcement concrete can be classified based on its fiber volume percentage as follows: (Behbahani et al., 2013).

- The very low volume fraction of SF (less than 1% per volume of concrete) which are used to control plastic shrinkage and as pavement reinforcement.
- The moderate volume fraction of SF (1% to 2% per volume of concrete) which have the ability to improve flexural toughness, impact resistance and further mechanical property of concrete.
- The high volume fraction of SF (more than 2% per volume of concrete) used for special applications like blast resistance structures.

In the class of high V_f , steel fiber has an exceptional mechanical property and can be utilized without continuous reinforcement; nevertheless, these composite materials are often used in highly specialized applications due to processing difficulty and high cost (Behbahani et al., 2013). Steel fiber cannot be used as the main reinforcement in reinforced and prestressed structural members, because it does not improve the flexural strength and it is discontinuous and randomly distributed throughout the concrete matrix. Therefore, the reinforcing performance of steel fibers is inferior to the reinforcing bar and considerably more expensive than the conventional rods (Balaguru and Shah, 1992). Many types of steel fiber are available as reinforcement. But mostly round steel fiber is broadly used in engineering applications. Generally, the SF used in concrete as reinforcement has a diameter ranging in between 5-500 μ m specific gravity 7.8, modulus of elasticity 200 GPa, failure 3-4% and tensile strength 1 to 3 GPa. Flexural strength and ultimate flexural strength are obtained through the using steel fiber of short (6.4 to 63.5 mm) and small diameters (0.15 to 0.91mm) (Mahadik et al., 2014).

2.3 Fresh state properties of geopolymer concrete

Workability is the easiness of working with the fresh concrete for handling, placing, compacting, and finishing. The geopolymer concrete has a viscous nature causing problems in the compaction; therefore, SCGC has been invented. The high slump in geopolymer concrete means reducing stickiness and thus increasing workability (Deb et al., 2014). The workability depends on superplasticizers and the kind of alkaline activators (Nematollahi and Sanjayan, 2014). The extra water increases the workability about 200% but decreases other properties about 27%. The workability increases about 115% by adding Admixture, however, reduce other properties by 25% (Aliabdo et al., 2016). Generally, the GPC mixtures demonstrated more cohesion than the OPC mixtures, due to the ingrained difference in the flow of the geopolymer matrix and the traditional concrete matrix (Khale and Chaudhary, 2007). Workability may be a very important concern for a fresh FA-based GPC due to its extreme viscosity. Therefore, the use of superplasticizers should be studied in practice. A large increase in resistance causes a decrease in workability of GPC with an enormous amount of GGBFS and less sodium silicate to sodium hydroxide ratio (Deb et al., 2014). The design of concrete requirements depends on several factors

including filling ability, passing ability (PA), and segregation resistance. For this, the coarse aggregate size should not override 20 mm. many fresh state tests such as slump flow, slump flow time (T_{500}), V-funnel, L-box, J-ring, and U-box are used to determine the flowability and passing ability of concrete. Table 2.1 shows their limits according to EFNARC guidelines.

Table 2.1 The limits of fresh state tests of concrete as per EFNARC (2002)

Test	Unit	Minimum Value	Maximum Value
Slump Flow	mm	650	800
T_{500} Slump Flow	sec	2	5
J-Ring	mm	0	10
V-Funnel	sec	6	12
L-Box H2/H1	mm	0.8	1.0
U-Box (H2-H1)	mm	0	30

Nuruddin et al. (2011) explored the influences of superplasticizer and sodium hydroxide alkaline solution on the workability of self-compacting geopolymer concrete by using different ratios of superplasticizer (3, 4, 5, 6, 7) % according to EFNARC (2002). They used a different molarity of Na_2SiO_3 and NaOH solution (8, 10, 12, 14) M with remaining the ratios of other materials constant for all mixtures. In their experimental work, dry low-calcium FA (class F) as per ASTM C618 was used. Their results were satisfactory according to EFNARC requirements. Increase in molarity from 8 to 14 led to reduction the workability, and low SP content (3, 4 and 5%) was poor in filling and passing ability and the workability results were not meet the requirements of EFNARC.

The use of nano-silica leads to decrease in the workability of concrete due to its great ability to absorb water (because it has very large SSA and their much finer dimensions compared to ordinary cement). The amount of NS above 3% volume content in the high-strength concrete mixtures cannot be used when the ratio of water to cement is low, because NS possesses a big water decrease property which counteracts full hydration reaction (Fallah and Nematzadeh, 2017).

Generally, incorporation of fibers makes the SCC less viscous and do not permit the aggregates to move easily, this lead to a decrease in the workability. In addition, high V_f of SF decreases the workability to values lower than those allowed in EFNARC (Khaloo et al., 2014). The slump values are from 65 mm to 100 mm for the fresh GPC, while it is between 28.2 mm and 27.5 mm for GPC with SF (Sunilkumar and Amol, 2015).

Abdullah et al. (2017, November) conducted a practical experiment to demonstrate the influence of SF on the workability of GPC from FA and alkaline solution. They presented that the workability values of the GPC specimens without HESF was 100 mm while the workability values of HESF specimens with ratios of 1%, 3%, 5%, and 7% by weight were between 30 mm to 60 mm.

2.4 Mechanical properties of geopolymer concrete

2.4.1 Compressive strength

Compressive strength is a fundamental characteristic of concrete depends on some factors like w/c ratio, the strength of cement and cementitious material, quality of concrete and quality control during concrete production, coarse aggregate size, and curing. The strength increases as the curing time and temperature increase. It can be obtained about 40 MPa to 50 MPa when the curing temperature is between 60°C to 90°C for a period ranging from 24 to 72 hours. Further, the compressive strength of GPC also depends on the smoothness of FA particles (smaller than 43 nm) (Van Chanh et al., 2008, November). Where, the strength increases by increasing the smoothness of FA particles. The concentration of silicon is important to determine the strength of alkali-activator. Thus, the existence of dissolved silicon in the water solution of sodium silicate clearly contributes to increasing of reaction velocity, therefore, this lead to the increase compressive strength (Komljenović et al., 2010). Maximum compressive strength was in the FA/GGBFS-based GPC with 30% GGBFS. Nevertheless, adding of 50% GGBFS is likely to decrease the strength at 28 days (Wardhono et al., 2017, September)

2.4.2 Bond strength

The bonding between the reinforcement bar and the concrete is an important characteristic of the structures of concrete which must be taken into account. Bonding stress acts at the interface of reinforcing steel bars and surrounding concrete and allows transferring of tensile stress from the bars into the concrete and vice versa, because of the adhesion between the bar and concrete (Doguparti, 2015). There are two types of bonding anchorage bond and flexural bond. Chemically, the geopolymer binder differs from the cement Portland binder. Therefore, studying the bonding between the reinforcement bars is very important to know the bonding strength between GPC and bar (Sarker, 2010).

2.4.3 Fracture property

The fracture mechanism is defined as the occurrence of failure and its spread through the structure. From a physical point of view, it is defined as separating the material into two or more parts, when enough stress is applied at the atomic level to break down the bonds that combine the atoms together. There are several reasons for fracture failure comprising, uncertainty in the loading, impact of environment, the defects of materials and design, and defects in construction and maintenance (Alyhya, 2016). Concrete is a brittle material having strength over 100 MPa may produce by conventional materials (Balaguru et al., 1992). Precipitation, shrinkage, and thermal movement are major causes of cracks in non-structural sections, whereas it occurs due to excessive tensile stress in structural sections (Olek et al., 2004).

Fibers are a natural or synthetic substance that is significantly longer than it's wide. It is utilized to improve the properties of concrete, such as compressive, flexural, toughness, ductility of post-failure, and crack control. Currently, SF is utilized to develop the fracture behavior of concrete. It possesses higher fracture energy than normal concrete (Peng et al., 2006). Since the binder in GPC is quite different from that available in ordinary Portland concrete, thus the interaction between each of the geopolymer and aggregate needs to be studied. Therefore, it is essential to explore the fracture parameters of GPC to comprehend its failure behavior.

2.4.4 Effect of NS on bond strength of SCGC

Improving the interfacial transition zone between aggregates and mortar as well as between aggregates and steel bars are the best ways to enhance concrete bond strength. It is clear that utilizing deformed bars can extremely improve the concrete-bars bond strength. There are three essential mechanisms that define the bond strength between the ribs adjacent to the reinforcing bar. These mechanisms are the bearing stresses against the faces of ribs (mechanical interlock), shear stresses, because of the adherence throughout the surface of the bar, and the friction between bumps of bars and the surrounding concrete. Lately, those ways were done by using pozzolanic materials like nano-silica. Many properties were not studied sufficiently well such as the bond strength of NS concrete. The best proportion of NS to increase the bond strength of 12 mm bars is 3% by weight, the improvement in bond strength reached 38.5% as compared to the same mixture without NS (Serag et al., 2017).

Adak et al. (2017) proved that using 6% of NS in the FA-based GPC (curing at room temperature 25 °C) gives better bond strength than those are free from the NS (at heat curing 60 °C, 48 h.) and conventional cement concrete (at water curing) for both mild and deformed steel bars.

2.5 Effect of NS on mechanical properties of SCGC

Nanomaterials have excellent physical, chemical, and mechanical properties that lead to a development of more effective materials than ones which are currently available. Currently, the nano-structured material technology increasing at an amazing quickness and will be applied widely with numerous materials (Li et al., 2004).

One of the most used nanomaterials is nano-silica; it has more pozzolanic nature which gives strength, durability, and impermeability to concrete. Ultra-fine particles of NS stop the voids of C-S-H structure which afford more homogenous spreading of hydrated products, which improves the strength and the durability of cement composites (Gopinath et al., 2012). nano-silica is being effectively used to reinforce geopolymer matrices to improve the mechanical properties; it works to increase the reactions of the geopolymer and also to fill the voids. NS was added to high-calcium FA-based GPC cured at ambient temperature to decrease the setting time and improve shear strength (Phoo-ngernkham et al., 2014). It is utilized in self-curing GPC in order to enhance the mechanical properties of metakaolin based GPC when

the curing temperature is 20°C (Pacheco-Torgal et al., 2011). Furthermore, strenuous efforts have been made to use NS in alkali-activated materials as alternatives to Portland cement to decrease the negative environmental influences of the cement industry. The use of nano-silica in cement composites has two vital problems that must be studied well; one of these problems is the non-distribution of particles regularly in the concrete mixture. Some researchers showed that the proper ratio of NS should be small (1-5 wt %) to prevent agglomeration of particles through blending (Al-Amoudi et al., 2004; Qing et al., 2007). However, others researchers have shown that the properties of concrete may be enhanced with dosages up to roughly 10 wt% if these particles are distributed positively in the initial cementitious mixture (Al-Amoudi et al., 2004; Ji, 2005; Cwirzen, 2010). The other problem related to the use of nano-silica in concrete is the high surface area that characterizes it, which leads to an increase its need for water and thus decrease the liquidity of concrete (Cwirzen, 2010; Qing et al., 2006).

2.5.1 Effect of NS on compressive strength of SCGC

There is limited literature available for the influence of NS on the compressive strength of GPC, perhaps the most prominent are:

Adak et al. (2014) conducted a Practical experiment to research the effect of adding different proportions of NS in low-calcium FA-based geopolymer mortar using various molar concentrations. They adopted four various ratios of NS addition (0%, 4%, 6%, 8% and 10% by mass). The results displayed that addition of 6% NA in geopolymer mortar improved the compressive strength at 28 days when cured at ambient temperature.

Deb et al. (2015) have tested the effect of NS on GPC using Low-calcium FA (class F) and blended with GGBFS and OPC in small percentages to hurry the curing at ambient temperature. In their experimental work, average particles diameter of FA (15 nm), a rate about 3% of the binder and sodium hydroxide (8 m) and sodium silicate were used. Several mixtures were taken in different proportions; every mix contained the same proportion of alkaline solution (40%) with a ratio of sodium silicate to sodium hydroxide of 2.0. Size of cube specimens (50 × 50 × 50) mm³ was cast and compacted by a vibrator. The specimens were cured at 20 ± 2 °C (room temperature) and at a relative humidity of 70 ± 10%. They found that the

compressive strength of ambient-cured geopolymer specimens improved with addition of NS at early ages. Furthermore, adding NS up to a dosage of 2% has led to increasing the compressive strength.

Gao et al. (2015) studied the influences of NS on compressive strength of eco-friendly alkali-activated GGBFS/FA mixtures. In their study, many samples with dissimilar NS content (0%, 1%, 2%, 3%) and slag/fly ash ratios (70/30 & 30/70) were taken. The specimens were tested at the ages of 3, 7 and 28 days respectively. The average of compressive strength was calculated for every six specimens. Researchers have found that increasing NS content up to 2% has benefited the compressive strength at curing ages of 3, 7 and 28 days, this percentage has set higher compressive strength with higher slag content. While that, NS content higher than 2% showed a negative influence.

Naskar and Chakraborty (2016) explored the influence of different ratios of NS in low-calcium FA-based GPC. They used the aggregate as a dry saturated surface and NaOH/Na₂SiO₃ as a solution of 16 M. At firstly, they cured the specimens for 48 hours and then treated at 60 °C for 48 hours. After that, it stored in the air until the testing. They determined the compressive strength of GPC for all mixtures without and with an addition of NS at 7, and 28 days. By casting the normal cubes specimens of size (150 × 150 × 150) mm. GPC specimens presented nearly 80% of the compressive strength at 7 days, but at 28 days the strength appeared to be reduced. Also, the addition of 3% and 6% did not offer satisfactory compressive strength at 7 and 28 days.

Nano-silica can be utilized to overcome the problem of heat curing of FA-based GPC and gives excellent mechanical properties, in this regard, Adak et al. (2017) have added 6% NS in FA-based GPC specimens and compared with two other specimens. One of which was geopolymer without NS and the other was a normal specimen containing OPC. After 24 h of casting, nano-silica modified geopolymer concrete samples were eliminated from the mold and cured at ambient temperature (27 ± 2°C). While the GPC samples without NS were cured at 60°C for 48 h with an oven. Further, these samples were reserved at ambient temperature till testing. The results displayed that the samples containing NS had higher compressive strength than others at different ages.

Assaedi et al. (2015) studied the effects of mixing procedures on mechanical properties of low-calcium FA (class F)-based GPC matrices containing NS by using the dry and the wet mixing methods for preparing geopolymer process. They used a blend of NaOH (purity 98% and 8 M) and Na_2SiO_3 grade D as an alkaline activator. The ratio of alkaline solution to FA and Na_2SiO_3 to NaOH was 0.75 and 2.5 respectively. For dry-mix process, nano-silica (dia. 18-25nm) was first added to the FA at the dosages of 0%, 0.5%, 1.0%, 2.0% and 3.0% by weight, and was dry-mixed for 5 min. to create the wet mix paste similar mixtures were prepared; but NS was added to the alkaline at first. After casting, all specimens were enclosed with nylon packaging and cured at 80 °C for 24 h in a furnace before demoulding. Then, they were placed under ambient conditions for 28 days. The two methods were compared. In the dry-mixing method, results showed that addition of 1% NS has improved the compressive strength by 28%.

Phoo-ngernkham et al. (2014) explored the influence of NS on GPC using FA as a binder; they concluded that increasing NS content led to a diminution setting time and improvement of mechanical properties. Also, they found by microstructure analysis that NS content up to 2% densities the matrix and increase the reaction product, but higher NS content showed negative effects.

2.6 Effect of SF on mechanical properties of SCGC

2.6.1 Effect of SF on compressive strength of SCGC

Ramkumar et al. (2015) used two mixes of geopolymer based on 50% FA and 50% GGBFS so that each mixture contains either crimped stainless steel fiber or crimped mild steel fiber, they compared it with the same mixture but without SF to demonstrate the influence of SF on GPC. Steel fiber had an aspect ratio of 60. They mixed the three materials with the dry state and then added the alkaline solution composed of Na_2SiO_3 and NaOH. The researchers concluded that the compressive strength increased by 2.25% when adding SF and was higher than the control mixture by 20%.

Sivakumar et al. (2014) have used glued steel fiber with length of 35 mm and diameter of 0.5 mm having l/d of 70 at various V_f of 0.5%, 1.0% and 1.5% in the GGBFS-based GPC activated by 12 M of NaOH. A special invented steam room was used by them to curing the samples at 75°C for 6 h. The results displayed that the

percentage of binder to the total aggregate of 0.3 and fine aggregate to coarse aggregate of 0.8 with 1.5% volume fraction of SF has obtained a maximum compressive strength of 54.77 MPa.

Yuvaraj and Srinivasan (2016) investigated the compressive strength of GPC. In their specimens, GGBFS was utilized as a binder with the addition of NaOH and Na_2SiO_3 as an alkaline solution. They used HESF of 60 mm and 30 mm length together in the specimens. They have observed that the specimen which consisted of 60% of 30 mm and 40% of 60 mm SF have given a maximum compressive strength (41.2MPa) and they also concluded that shorter steel fiber showed greater compressive strength.

Bernal et al. (2006, November) investigated the performance of GPC incorporating GGBFS as a binder and reinforced with SF. Their results showed that using of SF in the matrix reduced the compressive strength at early ages.

Ganesan et al. (2013) carried out a study on the influence of SF on the mechanical properties of low-calcium FA-based GPC. In their study, different volume fractions of crimped steel fibers having l/d of 66 mm and ultimate tensile strength of 800 MPa were utilized. They reported that utilization of crimped steel fiber in GPC slightly improves the compressive strength. Especially at 1% where this ratio gave the greatest compressive strength compared to other ratios.

Bernal et al. (2010) conducted a practical experiment on the effect of SF on the mechanical properties of GGBFS-based GPC and concluded that the use of SF reduced the compressive strength.

Sayyad and Patankar (2013) studied the effect of crimped steel fiber on low-calcium FA-based GPC activated by alkaline solutions ($\text{NaOH} + \text{Na}_2\text{SiO}_3$) with the solution to FA proportion of 0.35. They used a crimped steel fiber having l/d of 50 with V_f of 0.0% to 0.5% at an interval of 0.1% by mass. They concluded that the wet and dry densities of GPC composites increased with increase in SF content constantly. Abdullah et al. (2017, November) used the HESF in GPC using FA as a binder mixed with the alkaline activators. In their study, different amount of HESF 1%, 3%, 5% and 7% by weight were used for preparing GPC; all the specimens were cured at ambient temperature until testing. The results revealed that the compressive strength of GPC increased as the HESF increase. The maximum compressive strength gotten was about 87.83 MPa on the 14th day.

2.6.2 Effect of SF on fracture property of SCGC

Due to the brittle, low tensile strength, and strain capacity of GPC, fibers are used to increase the tensile strength and improve post-cracking behavior of the material where the fibers bind the slots of cracks (Gopalaratnam and Shah, 1987; Guerrero and Naaman, 2000). The idea of Insertion fibers as reinforcement in GPC is presented to enhance the properties of GPC such as durability, flexural strength, and fracture toughness. Several types of fibers such as steel, synthetic, and glass were used as reinforcement in GPC (Vijai et al., 2010). The main object of using fibers is to contain the cracks and improve the fracture toughness of the brittle matrix by working to seal the microcracks in the matrix. At the prefacing of microcracking, the bridging activity of fibers blocks the opening and development of cracks. This activity raises the demand for energy to propagate the cracks (Dias and Thaumaturgo, 2005; Reis, 2006; Reis, 2007). Specific studies have been done to investigate the effect of SF on the fracture properties of GPC including:

Ding and Bai (2018) studied the fracture energy, fracture toughness and flexural strength parameters of the GGBFS-based GPC containing steel fiber using three volume fractions of 1.0%, 1.5%, and 2.0%, and compared the specimens with others without SF through conducting three-point bending (TPB) test. The experimental results showed that the addition of SF meaningfully increased the fracture energy and fracture toughness. The fracture energy reached the largest value when the fiber volume content was 1.5%. A rough correlation between the equivalent and residual flexural strengths was also noted.

Deepa et al. (2013) conducted an experiment to define the fracture parameters of fiber reinforced geopolymer concrete (M30 grade) and they compared the results with that of conventional fiber reinforced concrete of the same grade using TPB test on notched prisms (100 x 100 x 500) with an effective span of 400 mm and notch depth to beam depth percentage of 0.4 (notch depth = 40mm). In GPC, cement was completely substituted by low-calcium FA. A blend of Na_2SiO_3 and NaOH solution was selected as the alkaline solution. According to the results, the fracture energy of GPC was more than Portland cement concrete by 80%. GPC also exhibited 10-40% more fracture toughness than the conventional concrete. The increase in fiber content has led to increasing the fracture energy and fracture toughness of both GPC and

normal concrete. Fiber reinforced geopolymer concrete specimens exhibited 10-40% more fracture energy than reinforced concrete specimens.

Bernal et al. (2010) made a comparison between specimens of Colombian alkaline-concrete based on an alkali-activated GGBFS and specimens of OPC type 1 in terms of the impact of incorporation steel fiber on its fracture toughness properties using TPB test with a loading rate of 3 mm/s. In their study, the alkali-activation has been completed with a water glass solution of Na_2SiO_3 with a chemical composition of 32.4% SiO_2 , 13.5% Na_2O and 54.1% of water and a solution modulus ($M_s = \text{SiO}_2/\text{Na}_2\text{O}$) of 2.4. The results revealed that the flexural toughness value of alkali-activated GGBFS was three times greater than the OPC at early ages of curing in both notched and continuous specimens.

Dahake and Charkha (2016) studied the effect of several types and aspect ratios of SF at a constant volume fraction of 2.5 % by the weight of cement on flexural strength of SCC specimens by using beams of (150 x 150 x 700) mm depending on one mix design with strength of 35 MPa (normal concrete). The result revealed that the flexural strength has enhanced with the addition of SF. The reason for this is that the fibers arrests microcracks in the concrete.

2.7 The combined effect of NS and SF on properties of SCGC

Currently, crumb rubbers are used as a composition of cement concrete. According to previous studies; many features of concrete greatly improve after adding crumb rubbers. However, crumb rubber concrete applications are limited due to low tensile and compressive strengths. For the possibility of improving these properties, Wang et al. (2018) have carried out a laboratory experiment by adding nano-silica and steel fiber by different percentage to this type of concrete. They concluded that the compressive and splitting tensile strength of crumb rubber concrete enhanced by using NS and SF as additives.

Their and Özakça (2018) conducted a laboratory experiment to analyze the combined effect of NS and SF on the compressive strength of alkali-activated GGBFS/FA concrete combined cold-bonded FA aggregate. The researchers relied on both NS having SSA of 170–230 m^2/g , and HESF with a yield strength 1500 N/mm, young modulus = 200 GPa, density = 7850 kg/m^3 , length = 30 mm, and $l/d = 54.55$. They used 0.2% of nano-silica together with different percentages of steel fiber (0.5, 1.0,

and 1.5%). The specimens were cured at ambient temperature. They have found that the incorporation of steel fiber did not markedly improve the compressive strength except when utilized with nano-silica. The maximum compressive strength of 40-56 MPa was reached at the combined use of 1% SF and 2% NS.

The researchers have noted that when adding steel fiber and nano-silica to the self-consolidating concrete, a reverse effect occurred in the workability, so they have increased the proportion of SP to keep within the limits of specifications. They also noted that the combined effect of 4% NS with 1.5% SF have given a better effect on hardened properties. As compared with the other used ratios in their experiment (Gorgis et al. 2016).

Elboghdadi et al. (2015) also explored the combined effect of NS and SF on the mechanical properties of concrete. In their study, NS with a particle size of 9 to 20 nm as part cement replacement by 1, 1.5, 2, and 4 and 0.45, 0.9, and 1.35% was used with HESF made of low carbon steel wire having a length of 30 mm and a diameter of 0.8 mm. Water to binder ratio (w/b) for all mixes was set at 0.40. A constant binder content of 450 kg/m³ was used for all mixes. The samples were reserved at ambient condition for 24 h. then they were demoulded and saved in 22–25 °C water until testing. The results presented that the optimum ratios of NS and SF were 2% and 0.9% respectively, this ratios led to improving the elastic modulus about 94%. The flexural strength improved about 88% for specimens of 2 % NS and 1.35% SF, compared to specimens without NS and SF.

Zhang et al. (2014) have used two methods according to ASTM C1018 and DBV-1998, respectively, by utilizing of TPB test to calculate the flexural toughness of the high-performance concrete containing FA, NS, and SF. They observed that the utilizing of SF in concrete had a great improvement on the flexural toughness indices (I_5 , I_{10} , I_{20} , I_{30}) and variation coefficients of bearing capacity of the concrete comprising 15% FA and 5% NA.

CHAPTER 3

EXPERIMENTAL PROGRAM

3.1 Materials

3.1.1 Fly ash and slag

Fly ash (FA) is a by-product produced from burning of the coal. It is finer than cement and consists of glassy-spherical particles. FA (class F) was utilized in this research as binder material according to ASTM C 618, with a fine ground glassy granular material produces when the iron blast furnace slag is suddenly cooled, called ground granulated blast furnace slag and represented by GGBFS. All mixtures contained 50% FA and 50% GGBFS by weight. The used FA and GGBFS are shown in figure 3.1a and 3.1b respectively. The physical properties and chemical compounds of each material are given in Table 3.1.

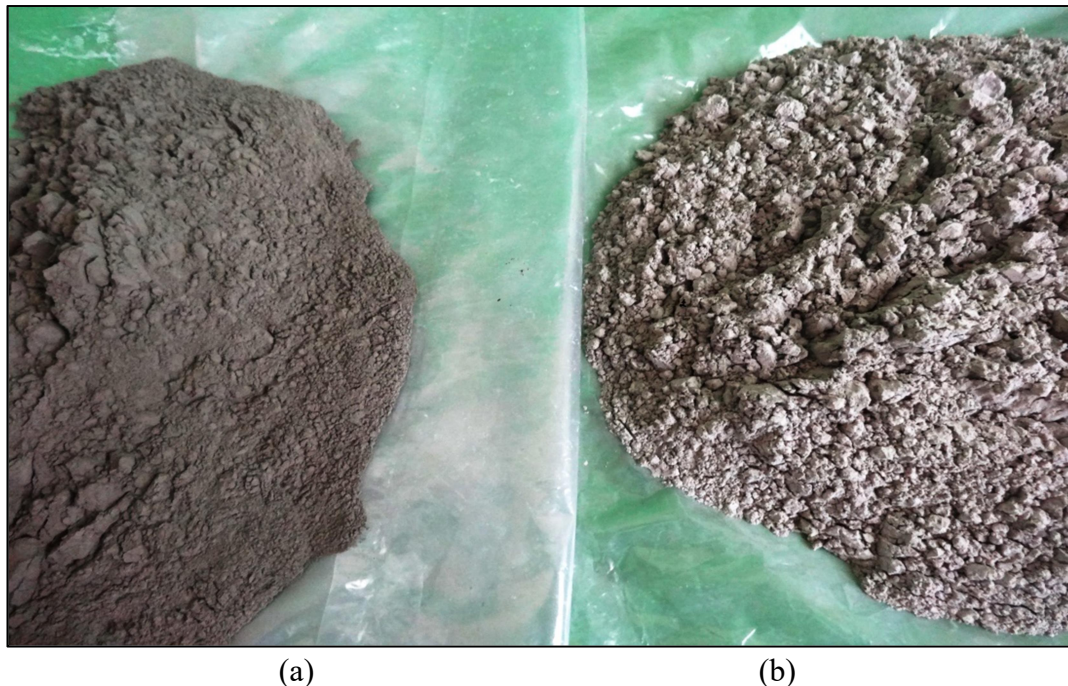


Figure 3.1 Photographic view of (a) FA (b) GGBFS

3.1.2 Nano-silica (NS)

Nano-silica is highly pozzolanic material containing very fine particles (100 nm) which is smaller than the particles of cement about one thousand times. NS used in this experimental study was manufactured by AEROSIL (domestic USA-CHEMTREC), (domestic Canada – CANUTEC) which is shown in figure 3.2. The NS Properties are shown in Table 3.1



Figure 3.2 Nano-silica used in SCGC

Table 3.1 Physical properties and chemical compounds of FA, GGBFS, and NS

Component	FA (%)	GGBFS (%)	NS (%)
CaO	1.60	34.12	-
SiO ₂	62.33	36.40	99.80
Al ₂ O ₃	21.14	11.39	-
Fe ₂ O ₃	7.15	1.69	-
MgO	2.40	10.30	-
SO ₃	0.10	0.49	-
K ₂ O	3.37	3.63	-
Na ₂ O	0.38	0.35	-
Loss of ignition	1.58	1.64	<1.00
Specific gravity kg/m ³	2.29	2.79	2.20
Blaine fineness (m ² /kg)	379	480	-

3.1.3 Steel fiber (SF)

The hooked-end steel fiber shown in figure 3.3 has been used in this research with two ratios ($V_f = 0.5\%$ and 1%). The properties of the SF are shown in Table 3.2.



Figure 3.3 Hooked-end steel fiber used in SCGC

Table 3.2 Properties of the used SF

Property	Results of SF
Description	Hooked-end
Length	30 mm
Diameter	0.75 mm
Aspect ratio (l/d)	40
Relative density	7840 kg / m^3
Ultimate tensile strength	1180 MPa

3.1.4 Aggregates

The coarse aggregate used in this study was the crushed limestone whose grain size is between 5 and 11 mm. As the fine aggregate, the crushed sand was used whose grain size is smaller than 4 mm. The preferred coarse and fine aggregates are shown in figure 3.4a and 3.4b, respectively.

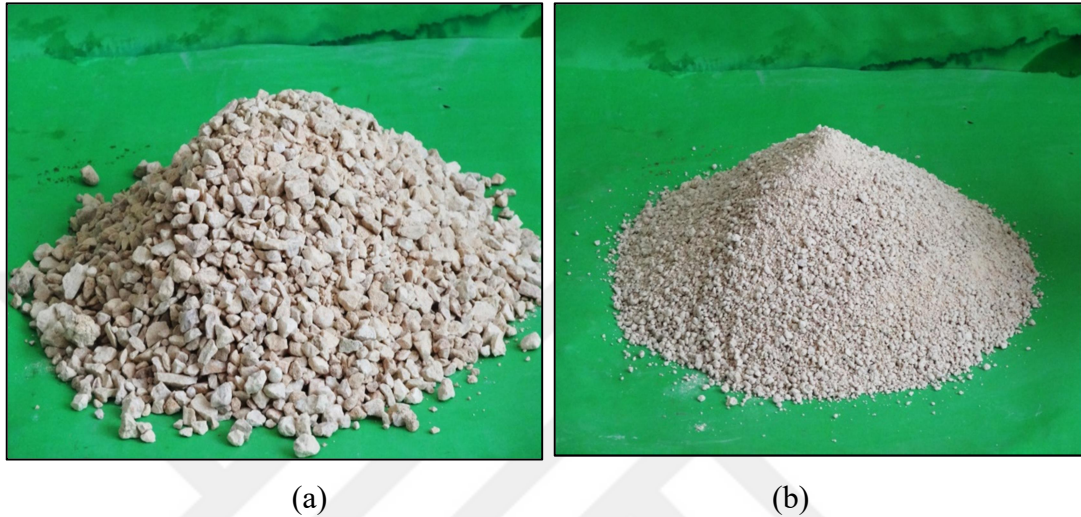


Figure 3.4 (a) coarse aggregate (b) fine aggregate

3.1.5 Superplasticizer

Superplasticizers are a chemical admixtures utilized to avoid from segregation of particles and improve the flowability. The addition of this admixture to concrete allows decrease of the water/cement ratio without reducing the workability. Polycarboxylates ether, shown in figure 3.5 with the specific gravity of 1.1 kg/m³ and density of 1.095 g/cm³ was utilized in this research as a superplasticizer.



Figure 3.5 Superplastisizer

3.1.6 Alkaline solution

In this study, a mixture of Na_2SiO_3 and NaOH has been used as an alkaline solution. It was prepared in the laboratory before 24 hours of concreting. The Na_2SiO_3 solution (Na_2O :13.7%, SiO_2 : 29.4, water: 55.9% by mass) was obtained from a local supplier (ZAG Kimya). The sodium hydroxide pellets were got from KOSFLAKE Company and its purity is $98\% \pm 0.5$. The pellets were dissolved in water to obtain 12M concentration of NaOH , which was found as the optimum concentration for the expected mechanical properties of SCGC (Memon et al., 2013). The prepared sodium silicate is shown in figure 3.6a, 3.6b and sodium hydroxide is shown in figure 3.6c, 3.6d.



(a)



(b)



(c)



(d)

Figure 3.6 (a) and (b) sodium silicate, (c) and (d) sodium hydroxide pellets

3.2 Concrete mix design and mixing procedure

The experimental work consisted of nine mixes of SCGC with a consistent binder content of 450 kg/m^3 ; all mixes contained an equal proportion of fly ash and slag (50% by weight) for each mixture as shown in Table 3.1. Initially, NaOH solution was prepared dissolving sodium hydroxide pellets in water. After a while, Na_2SiO_3 solution and NaOH solution were blended. This process was carried out 24 hours before casting, since the prepared alkaline activator solution should be used within 24-36 hours after mixing. Na_2SiO_3 to NaOH ratio was 2.5 in the experimental. This ratio was generally selected between 1.5 and 2.5 due to economic reasons (Olivia and Nikraz, 2012). The NS was incorporated with ratios of 1% and 2% by weight of the binder. SF was used with the ratio of 0.5% and 1%. For mixture designations, SF indicates the steel fiber, 0-0.5-1 indicates the SF volume fraction, NS indicates the nano-silica, and 0-1-2 indicates the NS content by weight of the binder. Aggregate, binder, alkaline amount, maximum grain size (D_{max}), steel fiber length, volume and aspect ratio affect fresh and hardened properties of SCGC specimens. The mixing sequence was as following; dry components; coarse aggregates under saturated surface dry condition, fine aggregates, FA, GGBFS, and NS were added and mixed for 2.5 minutes. The prepared alkaline solution was added, then, superplasticizer and extra water were added in one minute simultaneously and thereafter they were swiftly mixed for two minutes. After that, SF was added to the mixture. To ensure homogeneity and uniformity, the fresh concrete was mixed during extra 3 minutes. The complete mixing procedure is shown in figure 3.7. Moreover, molds of all specimens before and after casting are shown in figure 3.8a and 3.8b, respectively.

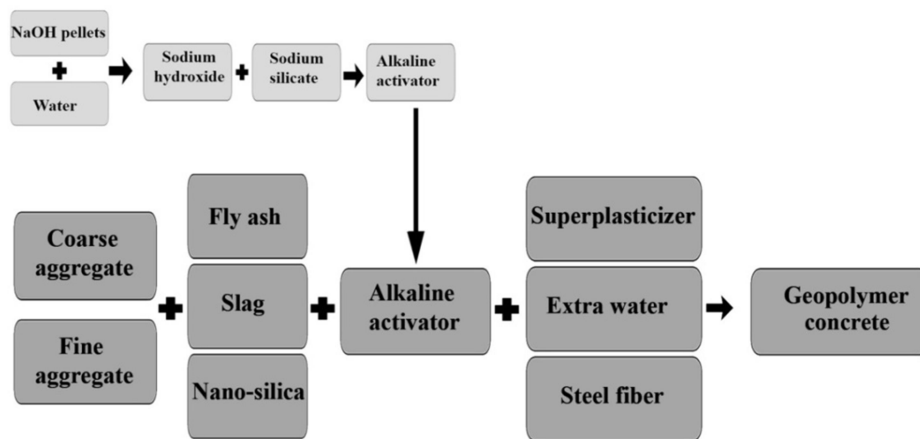


Figure 3.7 The procedure of preparing alkaline activator and GPC



(a)

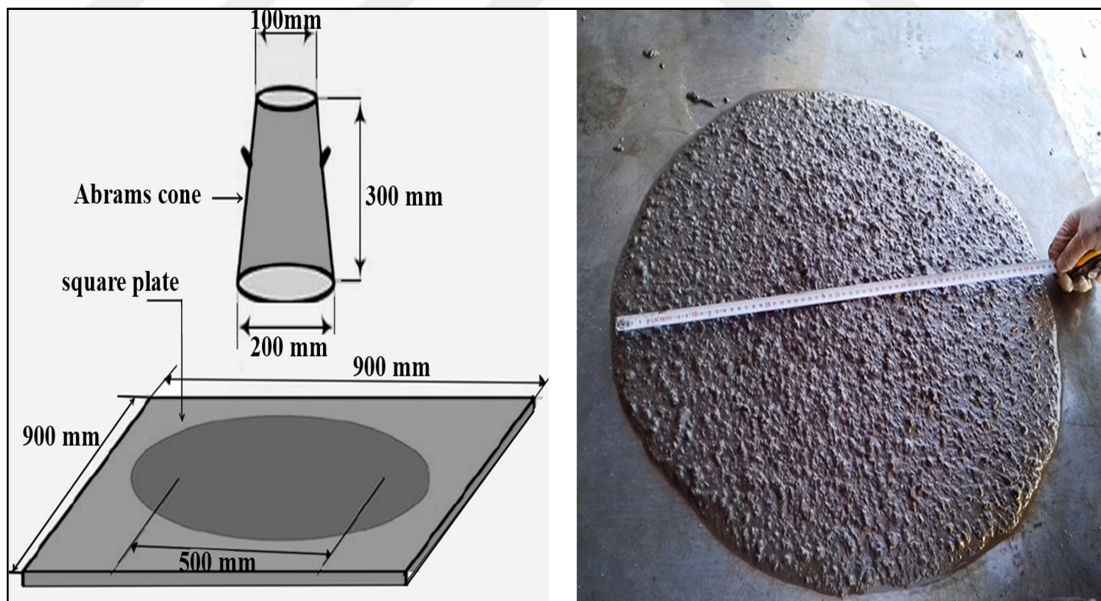


(b)

Figure 3.8 The moulds used and casting of hardened state specimens

3.3 Fresh state tests

The fresh state tests of SCGC were done immediately after the mixing process for each mixture which controls the requirements of flowability, filling ability, and passing ability without separation and/or bleeding. The slump flow, V-funnel, and L-Box tests were conducted to measure the flowability, filling ability, passing ability of SCGC specimens, respectively, according to the standards of EFNARC committee (2005). In the slump flow test, flow diameters in radial direction were measured as shown in figure 3.9. Moreover, T_{500} test, which measured the duration flow until 500 mm diameter, was made in slump flow test. In the V-funnel test, the section was totally filled with GPC, and then the concrete was let to discharge in order to record the discharge time. Application of V-funnel is shown in figure 3.10. Indirectly, the viscosity can be measured by V-funnel and T_{500} slump flow using the rate of flow. In the L-Box test, the passing ability between narrower openings (41 ± 1 mm) was calculated which is shown in figure 3.11. Table 4.1 illustrates the upper and lower limits for the fresh state properties of SCC mixes according to the EFNARC standards.



(a)

(b)

Figure 3.9 Slump flow tools and testing

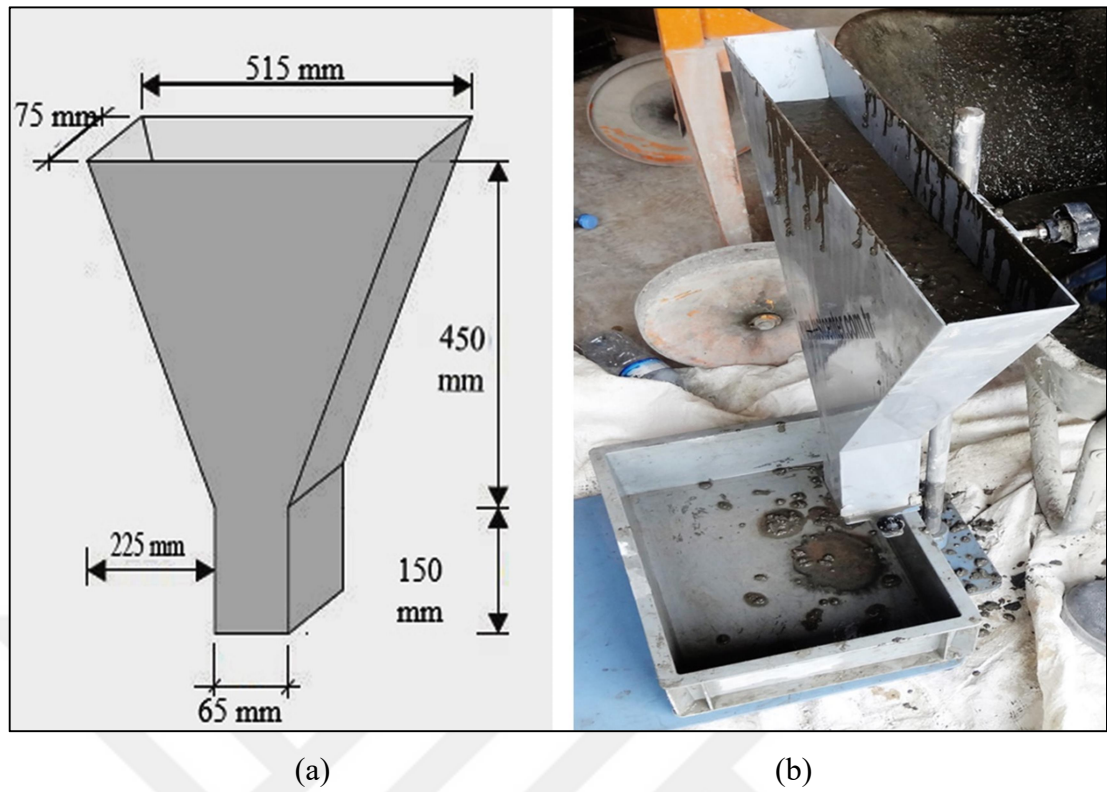


Figure 3.10 V-funnel details and testing

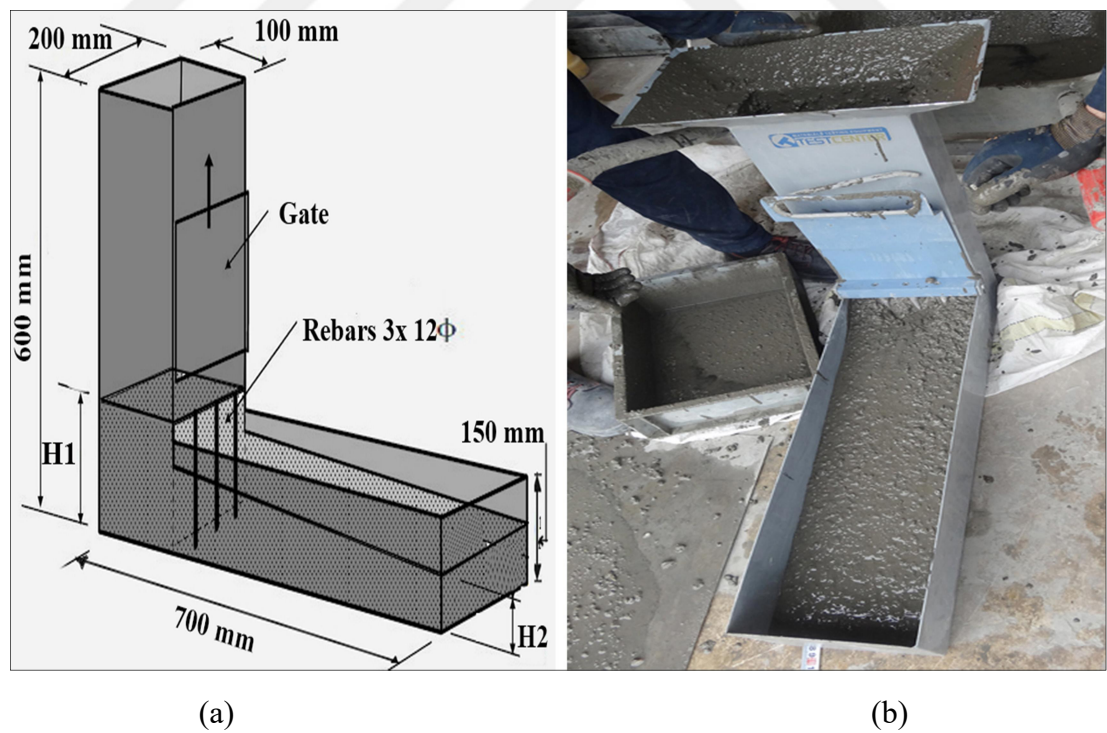


Figure 3.11 L-Box details and testing

Table 3.3 Mixture proportions of self-compacting geopolymer concrete

Mixture	Binder	Na ₂ SO ₃ +NaOH	FA	GGBFS	NS	SF	Fine Agg.	Coarse Agg.	Molarity (M)	SP	Extra water
	kg/m ³	kg/m ³	kg/m ³	kg/m ³	kg/m ³	kg/m ³	kg/m ³	kg/m ³		%	%
SF0NS0	450	225	225	225	0	0	865.61	742.88	12	5	8
SF0NS1	450	225	222.75	222.75	4.5	0	862.65	740.34	12	5	8
SF0NS2	450	225	220.5	220.5	9	0	859.69	737.80	12	5	8
SF0.5NS0	450	225	225	225	0	39.2	865.61	742.88	12	5	8
SF0.5NS1	450	225	222.75	222.75	4.5	39.2	865.61	742.88	12	5	8
SF0.5NS2	450	225	220.5	220.5	9	39.2	865.22	742.54	12	5	8
SF1NS0	450	225	225	225	0	78.4	864.83	742.21	12	5	8
SF1NS1	450	225	222.75	222.75	4.5	78.4	865.22	742.54	12	5	8
SF1NS2	450	225	220.5	220.5	9	78.4	864.83	742.21	12	5	8

3.4 Curing of the SCGC specimens

In order to preserve the alkaline solution from evaporation, the specimens were covered with plastic bags for 24 hours. Then, the specimens were placed in an oven for 48 hours at 70 °C, as shown in figure 3.12. Thereafter, the specimens were demoulded and placed in the ambient laboratory environment for 28 days of hardened state tests. Three similar specimens were produced for every test and the average of the test results was calculated.



Figure 3.12 The furnace used to curing of SCGC specimens

3.5 Hardened state tests

The hardened state tests were executed to study the combined effects of NS and SF on the mechanical performance of the SCGC. Compressive strength tests were conducted on cubes with dimensions of 100x100x100 mm. The compressive strength values were calculated according to ASTM C39 standard. Compressive strength test procedure is shown in figure 3.13.

$$f'_c = \frac{P}{A} \quad (3.1)$$

Where f'_c , is the compressive strength of specimens (MPa), P is the maximum load (kN) and A is the cross-sectional area of specimens (mm²).



Figure 3.13 A specimen under compressive strength machine

The bonding strength between the concrete and reinforcement bar was determined according to RILEM RC6. The surface of the pullout specimens should be flat to ensure uniform distribution of the load. Therefore, the surface of the specimens was coated with a layer of gypsum. The pullout test specimen dimensions are shown in Figure 3.14.

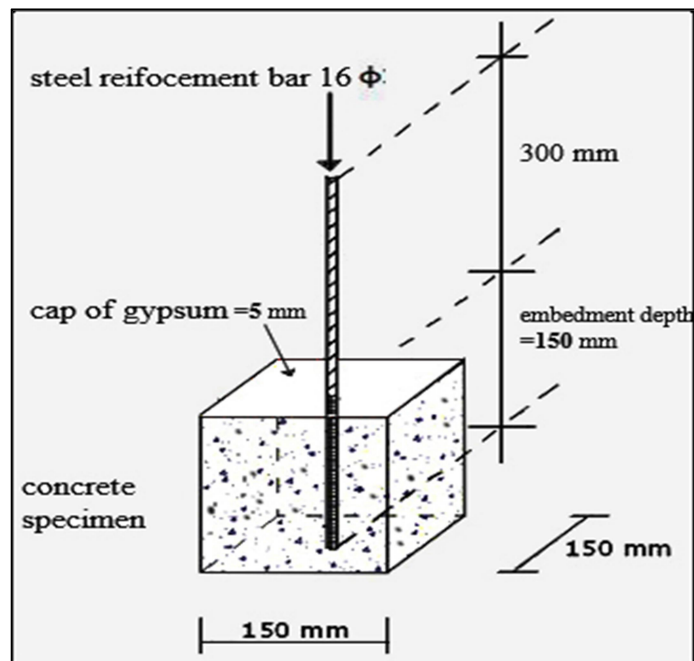


Figure 3.14 Dimensions of the pullout test specimen

Figure 3.15 displays the pullout test set up and a tested specimen under the pullout test. The bonding strength (τ) was calculated by equation 3.2 which is division of the tensile force by the surface area of the rebar planted in GPC:

$$\tau = \frac{F}{\pi \times d \times L} \quad (3.2)$$

Where τ , F , d , L are the bonding strength (MPa), the tensile load (N), the diameter of the bar (mm), and the planted length of rebar in GPC (mm), respectively. In this study, d was 16 mm and L was 150 mm.

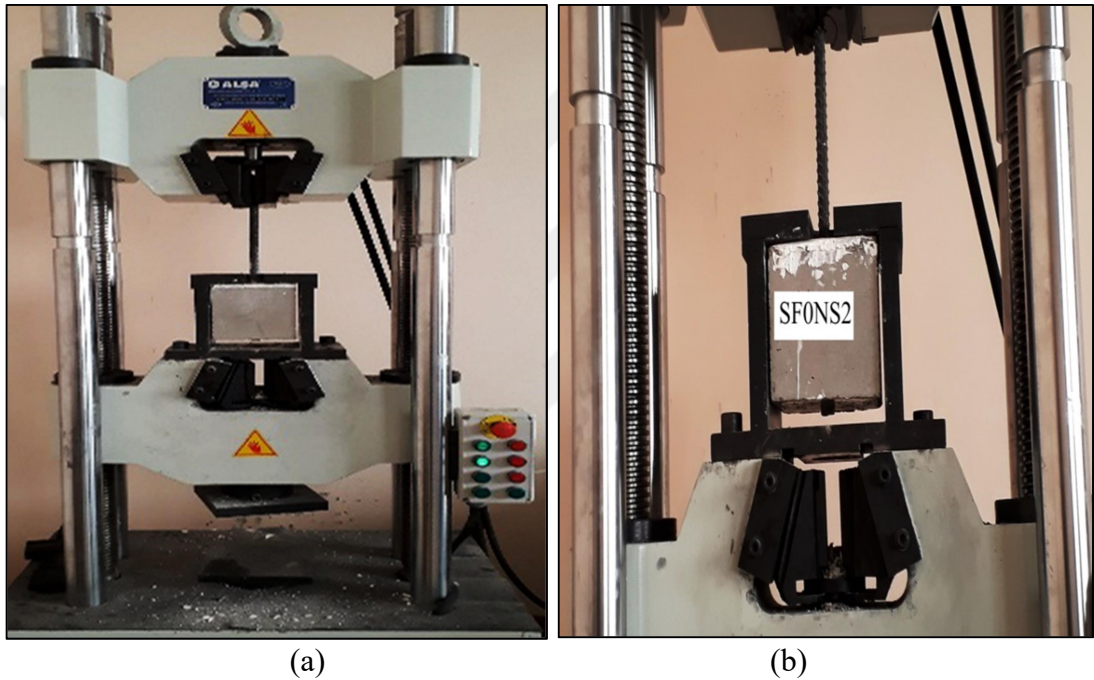


Figure 3.15 (a) pullout test set-up (b) SCGC specimen under the pullout

Three-point bending tests were conducted on notched prismatic specimens with dimensions of 100x100x500 mm by a machine called Instron 5500R, which is closed-loop displacement controlled loading machine and compatible with RILEM 50-FMC/198 Committee. Initially, notches were performed at the bottom mid-point of the specimens with a width of 3 mm and height of 40 mm. At mid-span of the notched specimens, the vertical displacement was measured by using a linear variable displacement transducer (LVDT). The test set-up and details of specimen under three-point bending tests are shown in Figure 3.16a and 3.16b, respectively. In this test, the loading rate has relied upon 0.02 mm/min under displacement control.

The net flexural strength (f_{flex}) of all specimens was calculated by the equation 3.3 (Akçay and Tasdemir, 2009).

$$f_{flex} = \frac{3P_{max}L}{2b(d-a)^2} \quad (3.3)$$

Where P_{max} is the peak load (N), L is the span length (mm), b is the width of the specimen (mm), d is the depth of specimen (mm), and a is the depth of the notch (mm).

Fracture energy (G_f) represents the energy amount required to create a crack in the binder paste matrix. Through the three-point bending test and using the equation 3.4 which is proposed by RILEM, the G_f of the prismatic specimens was calculated.

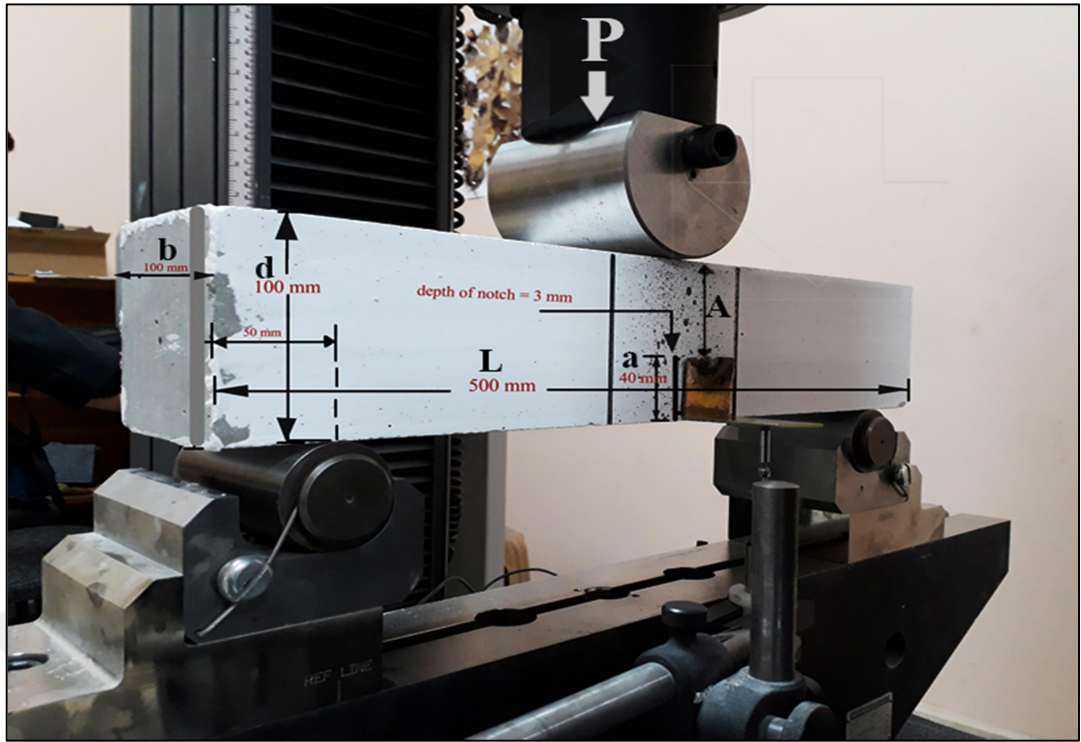
$$G_f = \frac{(w_o + mg\delta_s)}{A_{lig}} \quad (3.4)$$

Where w_o is the area under the load-displacement curve (N-m), m is the mass of the beam (kg), g is the acceleration caused by gravity (9.81m/s^2), δ_s is the specific displacement (m), and A_{lig} is the area of the ligament (m^2).

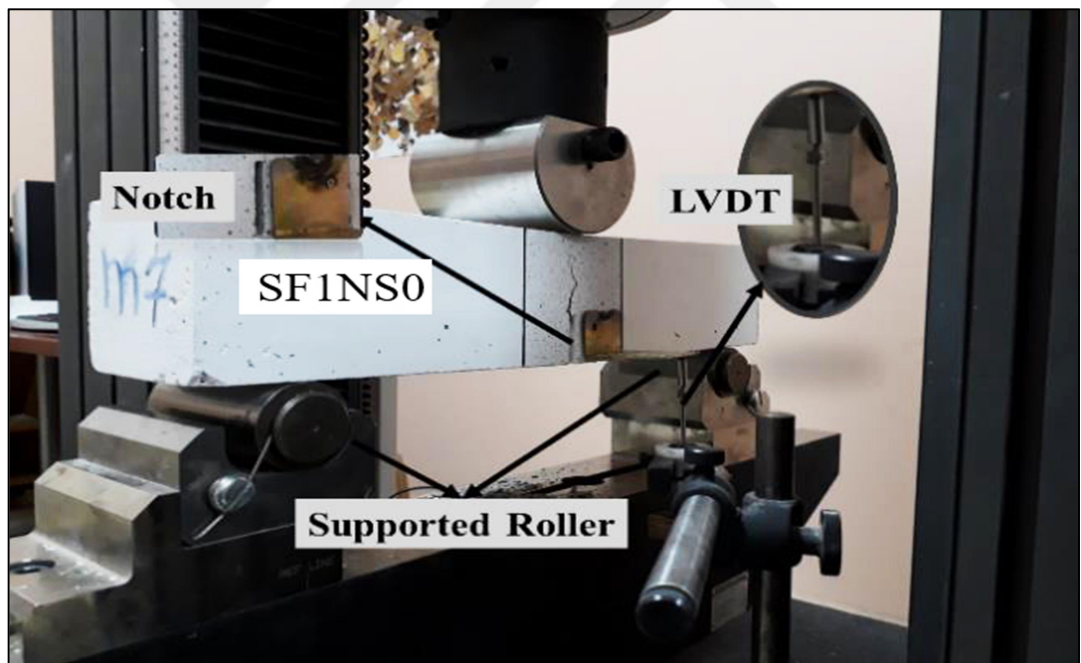
Moreover, the critical stress intensity factor (K_{IC}) was calculated using equation 3.5 (Peterson, 1980) for each beam specimens:

$$K_{IC} = \frac{3P_{max}l}{2bd^2} \sqrt{a_o} (1.93 - 3.07A + 14.53A^2 - 25.11A^3 + 25A^4) \quad (3.5)$$

Where P_{max} is the peak load, l is the span length, b is the width of specimens, d is the depth of specimens, a_o is the depth of the notch, and A is the ratio of notch depth to specimen depth.



(a)



(b)

Figure 3.16 (a) Test set-up and details of specimen (b) specimen under TPB test

CHAPTER 4

EXPERIMENTAL RESULTS AND DISCUSSIONS

4.1 Fresh state properties

Flowability and passing ability test results of the SCGC have satisfied the standards of EFNARC. Flow diameters of SCGC mixes were observed to be higher than the minimum flow diameter of 550 mm as shown in Figure 4.1, and no segregation was observed in the SCGC mixes. Slump flow diameter results also achieved EN 12350-8 specifications which state that the minimum slump flow diameter is 600 mm. investigation of the common influence of NS and SF on the fresh state performance of SCGC is one of the purposes of this research. Therefore, the influence of these materials on the flowability and passing ability characteristics of SCGC were studied in details.

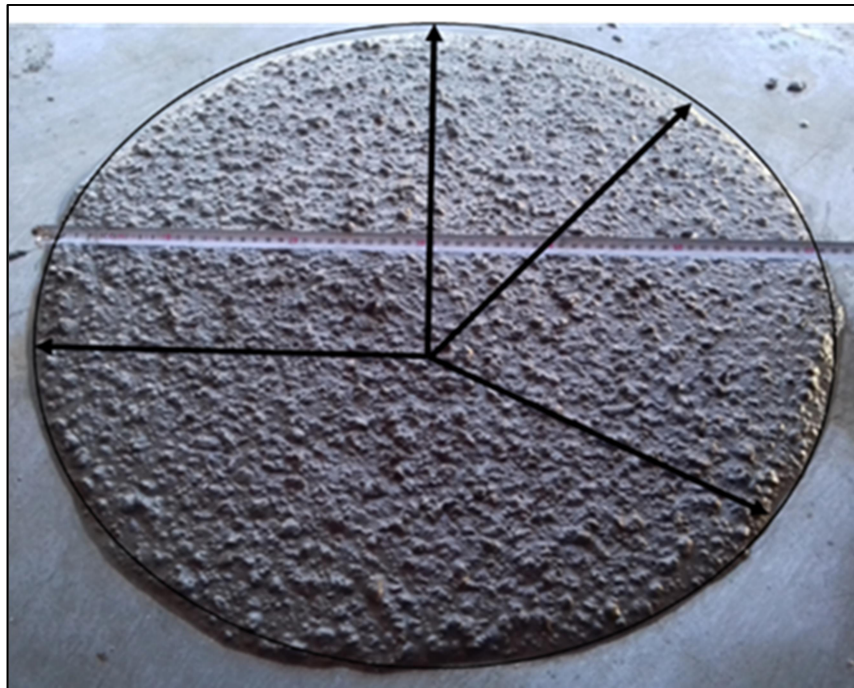


Figure 4.1 Slump flow diameter of SCGC

4.1.1 Effect of NS and SF on slump flow diameter

Experimental results showed that all slump flow diameter values were compatible with EFNARC specifications as shown in Table 4.1. Slump flow diameter results are shown in figure 4.2. It has been noted that the combined effect of NS and SF led to reduction of the slump flow diameter significantly. Lowest slump flow diameter (664 mm) was obtained for the mix with the highest amount of both nano-silica (2%) and steel fiber (1%). While the highest slump flow diameter (709 mm) was achieved for the mix without NS and SF. For non-fibrous mixes, the incorporation of NS led to reduction of the slump flow diameter from 709 mm (without NS) to 695 mm (1% NS) and 680 mm (2%NS). Also, the use of SF in the mixes has decreased the slump flow diameter of the mixes without NS from 709 mm (0%SF) to 693 mm (0.5%SF) and 687 mm (1%SF). Addition of 1% SF reduced the slump flow diameter less than 2%NS.

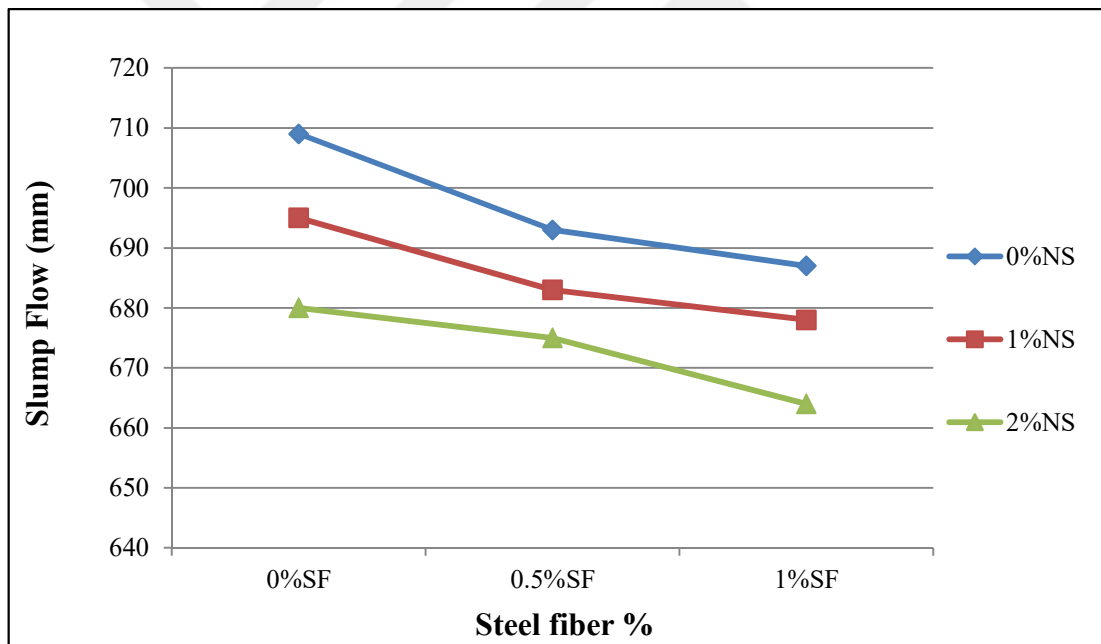


Figure 4.2 Effect of NS and SF on the slump flow diameter

4.1.2 Effect of NS and SF on the slump flow time

In general, T_{500} durations were satisfactory for both EFNARC specification and EN12350-8 standard which state that the T_{500} duration should be between 2-5 seconds. The results show that the nano-silica affects the T_{500} duration more than steel fiber. Mostly, the combined use of NS and SF increases the T_{500} duration as in

slump flow results, where the highest T_{500} duration (3.63s.) was recorded in the mixture containing the highest amount of nano-silica (2%) and steel fiber (1%). regarding the non-fibrous mixtures, T_{500} durations were 2.66s, 2.98s, and 3.23s with 0%NS, 1%NS, 2%NS, respectively. For the mixtures without NS and with 0%, 0.5%, and 1% steel fiber, T_{500} durations were 2.66s, 2.72s, and 2.83s, respectively. Figure 4.3 indicates the combined effect of NS and SF on the T_{500} duration.

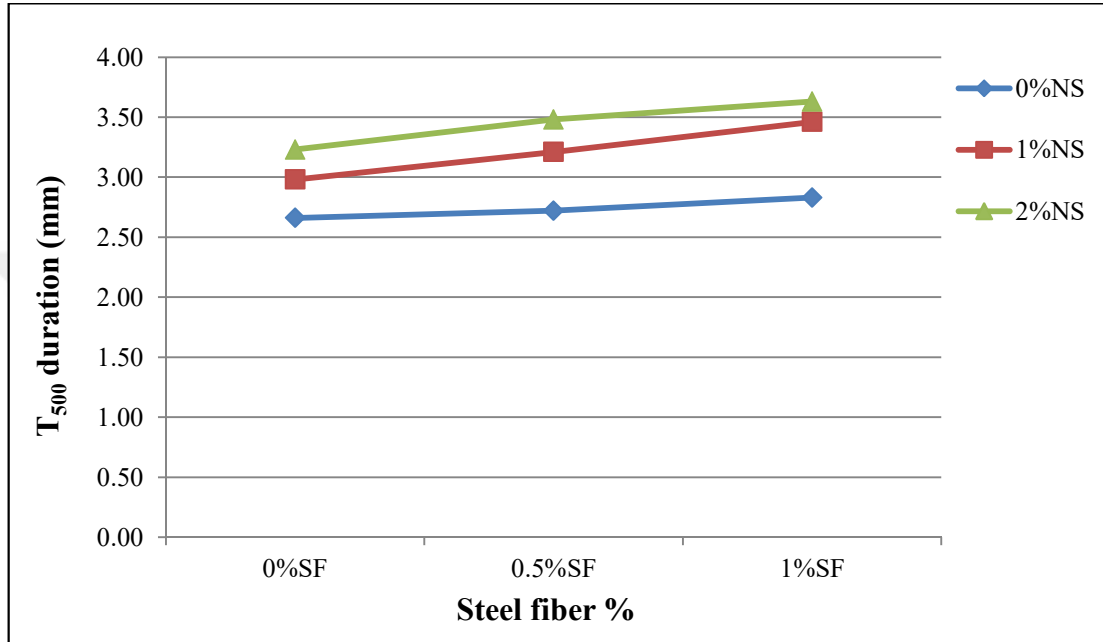


Figure 4.3 Slump flow duration versus NS and SF relationship

4.1.3 Effect of NS and SF on V-funnel flow time

Mainly, V-funnel test is utilized to calculate the filling ability of SCC. Moreover, this test is used to assess the ability of concrete to flow through the constrained areas the presence of any blocking and segregation.

In this test, it was observed that the results of discharge time from V-funnel sections were similar to the results of T_{500} . The discharge time for the non-fibrous mixes was measured as 10.84s, 13.24s and 16.63s for the 0%NS, 1%NS, and 2%NS, respectively. The discharge time of the specimens without NS was also measured as follows: 10.84s, 12.83s, and 13.76s for 0% SF, 0.5%SF, and 1% SF, respectively. Therefore, the influence of NS on discharge time was more than the influence of SF. As shown in Figure 4.4 the highest discharge time (18.5) was found in the mixes containing 2% NS and 1% SF.

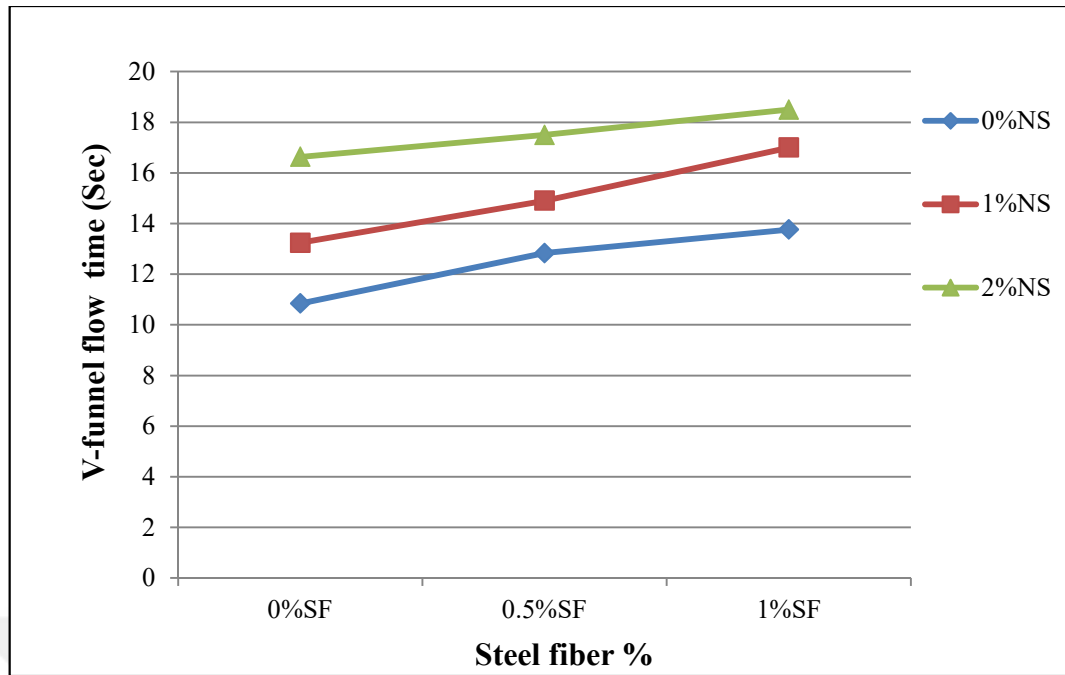
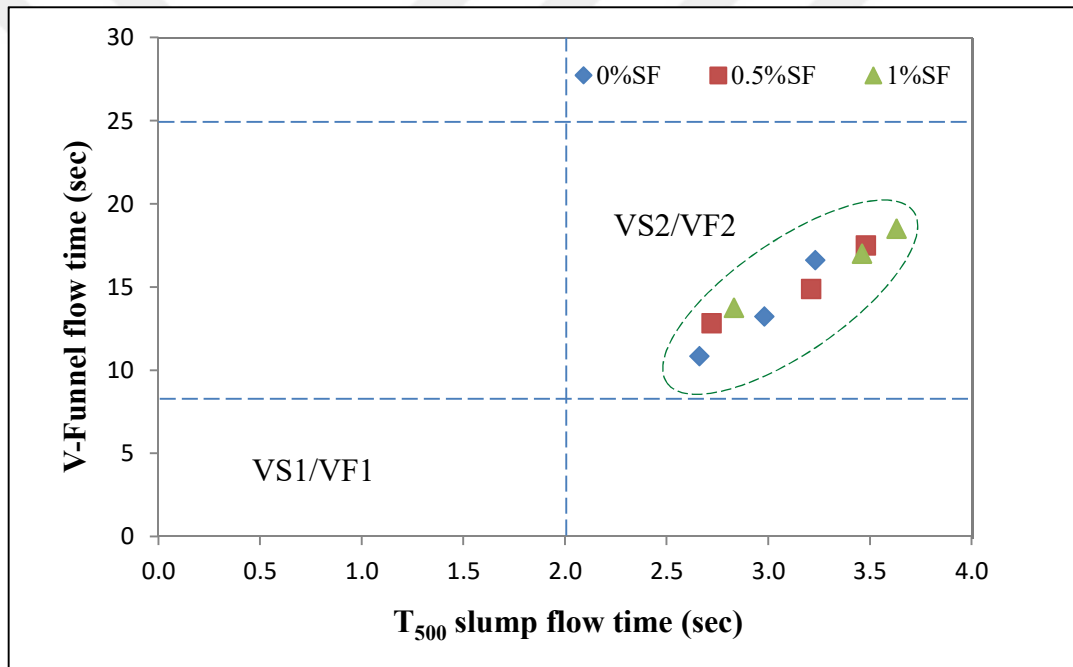


Figure 4.4 The combined effect of NS and SF on V-funnel

EFNARC states that VS1/VF1 viscosity class possesses the filling ability even in crowded reinforcements but it is liable to bleeding and segregation. According to the experimental results obtained, all mixes were in the range of VS2/VF2 viscosity class. This class has good bleeding and segregation resistance and low formwork pressure; however, it has insufficient surface finish properties and it may suffer from the stoppage of the SCGC mixes. Results indicated that the higher percentage of nano-silica extended the discharge time which may cause inadequate filling ability, but it is useful for the prevention of bleeding and segregation. EN12350-9 standard states that the discharge time of the V-funnel should be smaller than 15 seconds to ensure good filling ability. The discharge time of all mixes containing 2% NS was higher than 15s that led to reduction of the filling ability of SCGC considerably. It is important to note that the discharge time of the mixes without NS and with 1% NS was lower than the standard limit value of 15 seconds, except the mixes containing 1% NS and 1% SF. Figure 4.5 shows the viscosity classes based on the relationship between V-Funnel and T5₀₀ slump flow according to EFNARC specification.

Table 4.1 Slump flow, viscosity, and PA classes as per EFNARC specifications

Slump flow classes		
Class	Slump flow dia. [mm]	
Slump Flow 1	550 - 650	
Slump Flow 2	660 - 750	
Slump Flow 3	760 - 850	
Viscosity classes		
Class	V-funnel time [sec]	T ₅₀₀ [sec]
VS1 / VF1	≤ 8	≤ 2
VS2 / VF2	9 to 25	> 2
Passing ability classes		
PA1	≥ 0.8 for two rebar	
PA2	≥ 0.8 for three rebar	

**Figure 4.5** The relationship between V-funnel and T₅₀₀ flow time

4.1.4 Effect of NS and SF on L-box height

Passing ability values of SCGC mixtures should be equal or higher than 0.8 in order to obtain sufficient passing ability according to both EFNARC specification and EN12350-10 standard. In the L-Box test with three bars, passing ability of the mixtures between narrower openings of bars (41 ± 1 mm) was measured by dividing the concrete heights in the horizontal part to the heights in vertical part (H_2/H_1). As shown in Figure 4.6, all mixtures have a satisfactory passing ability (more than 0.8). The highest passing ability (0.96) was measured in the mixtures without NS and SF.

PA values for the specimens without NS were 0.96, 0.92, and 0.9 for 0%, 0.5% and 1% SF mixes, respectively. Regarding the specimens without SF, PA values were measured as 0.96, 0.91, and 0.88 for the specimens with 0%NS, 1%NS, and 2%NS, respectively. The lowest PA value was 0.82 which is observed in the mix containing 2% NS and 1% SF. It can be noted that as the amount of NS and SF increased further, PA criterion may not be satisfied for the SCGC mixes.

Through the results obtained from the fresh state tests as shown in Table 4.2, it has been calculated that the combined use of NS and SF in the SCGC led to reduction of slump flow diameter, T_{500} duration, V-funnel discharge time, and L-Box. However, even in the highest amount of NS (2%) and SF (1%), the self-compacting geopolymer mixtures satisfied the criteria of flowability and passing ability according to EFNARC specifications and BS EN 12350 standards. It has also been concluded that utilization of the higher amount of NS has improved resistance of SCGC to segregation and bleeding and the mixtures containing NS were more cohesive than the mixes without NS.

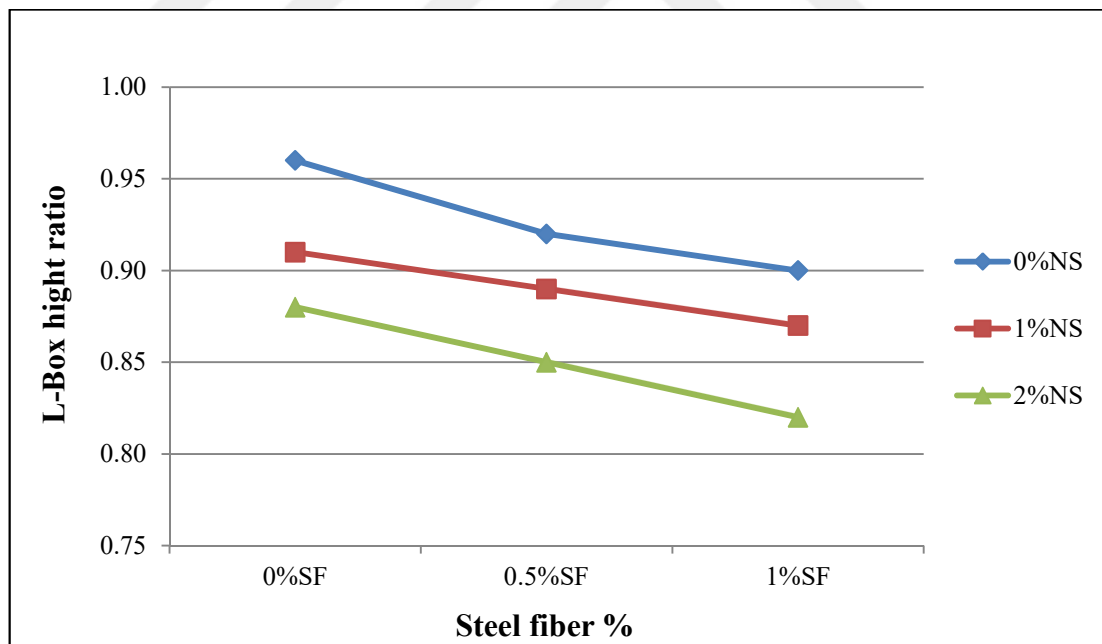


Figure 4.6 The variation of L-Box height ratio with NS level and SF

4.2 Hardened state properties of SCGC

4.2.1 Compressive strength

Figure 4.7 displays the influence of both NS and SF on compressive strength of the specimens. Specimens without NS have higher compressive strength values than specimens containing NS. This result is due to the extreme self-dehydration and cracks in the matrix caused by the non-interaction of some NS particles, thereby reducing the strength of the specimens (Belkowitz et al., 2015; Çevik et al., 2018). However, it was observed that the existence of SF slightly improves the compressive strength values. Increase in the strength values was found to be more than 5% and 7% for 0.5% and 1% steel fibrous specimens, respectively. The compressive strength of specimens containing NS has enhanced with addition of SF; because the decreasing effect of NS on the compressive strength has been recompensed by the SF inclusions. For instance, compressive strength of the control specimen (0% NS and 0% SF) and the specimen containing the highest amount of NS (2%NS) and (1%SF) are very close to each other.

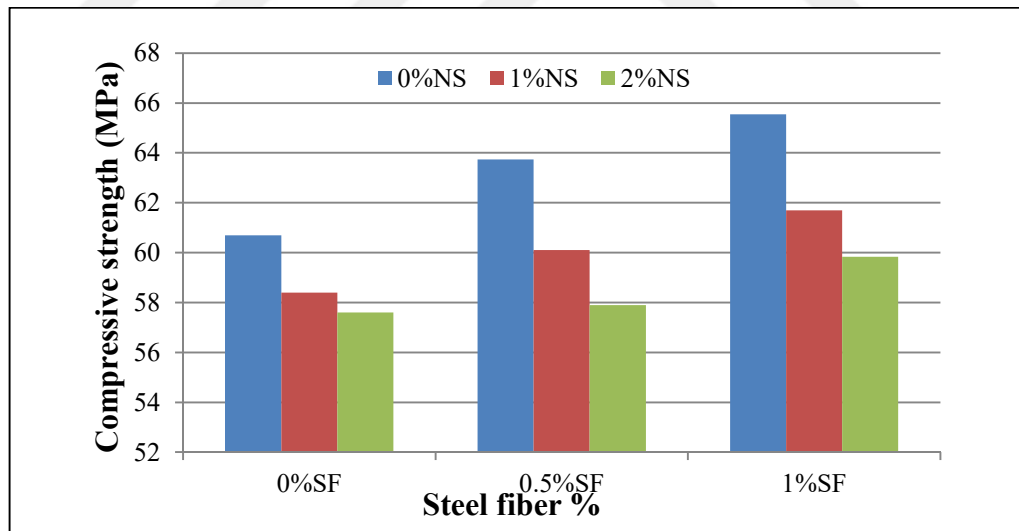


Figure 4.7 Influence of NS and SF on compressive strength

4.2.2 Bond strength

Nano-silica has slightly improved the bond strength of the specimens. In addition, increasing in SF volume fractions significantly improved the bond strength. The highest bond strength was observed to be 25.4% for the specimens containing 2%NS and 1%SF as compared to control specimens. The positive influence of SF on the

bond strength was noted to be more than the influence of NS. Figure 4.8 indicates the combined influence of NS and SF on bond strength.

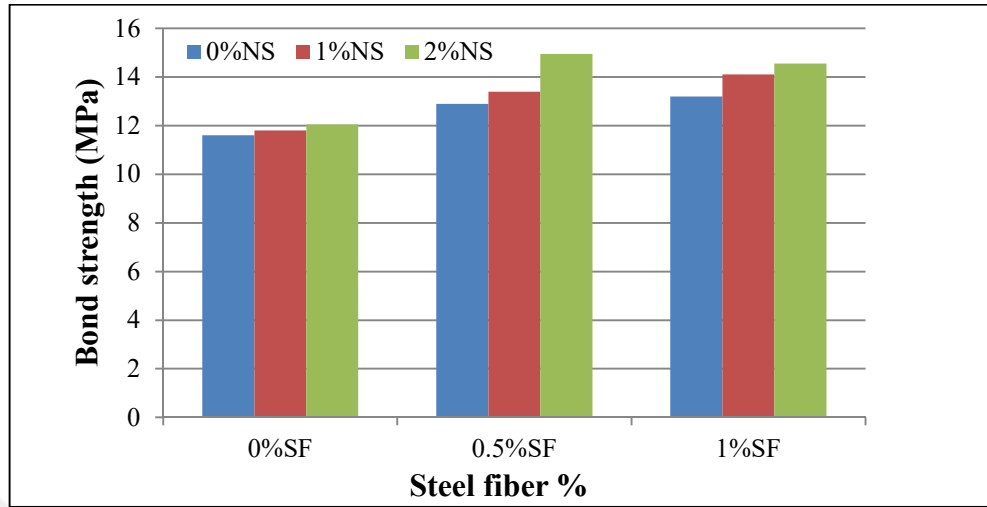


Figure 4.8 The together influence of NS and SF on bond strength

Baran et al. (2012) identified that SF improved the pullout resistance of strands by governing the spread of cracks within the concrete blocks. Also, they concluded that the confinement level at the strand-concrete interface increased with an increase in the SF volume fraction which improved both friction and the bond strength. They found that addition of SF can provide bond strength enhancement more than 30%. The studies concerning the bond strength between rebar and concrete are related with Ordinary Portland Cement (OPC) concrete. However, there is a limited study performed on the bond strength of SCGC specimens containing NS. This study may highlight the effect of use of NS and SF on bond strength of the SCGC specimens.

Abu-Lebdeh et al. (2011) explained that the quality of cement matrix is an important parameter for the bond strength and tensile strain capacity of very-high strength concrete, because of the micro-filling influence and pozzolanic activity. NS may develop the pullout capacity of the reinforced concrete structures (Gencel et al., 2011). After the failure of SCGC specimens without SF, the rebar has separated from concrete completely. However, for the specimens containing SF, structural rebar remained to survive in the cracked matrix. Similar results have also been observed in former studies.

Krstulovic-Opara et al. (1994) reported that pullout strength increased by 10–20% when 1% SF was added by the volume of concrete.

Harajli and Salloukh (1997) reported that addition of 2% SF to the reinforced concrete beam specimens increased the bond strength up to 55% as compared to non-fibrous specimens. Also, with the further increase in SF volume fraction, the bond strength increased more than two or three times. In view of the results regarding the bond strength of the OPC stated in the literature, it can be said that the combined effect of NS and SF improves the bond strength of SCGC specimens further. Figure 4.9 indicates the typical failure patterns of the SCGC specimens after pullout tests.

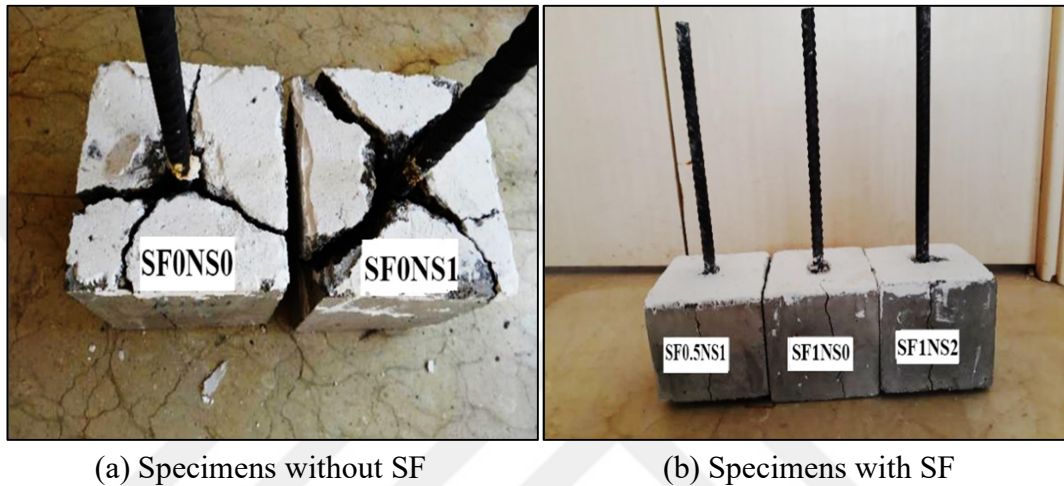
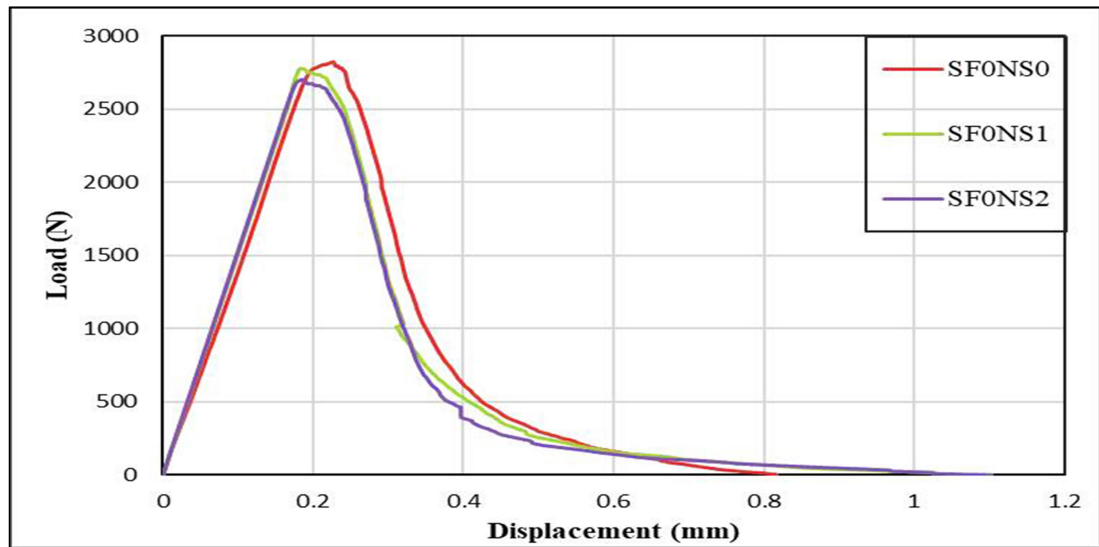


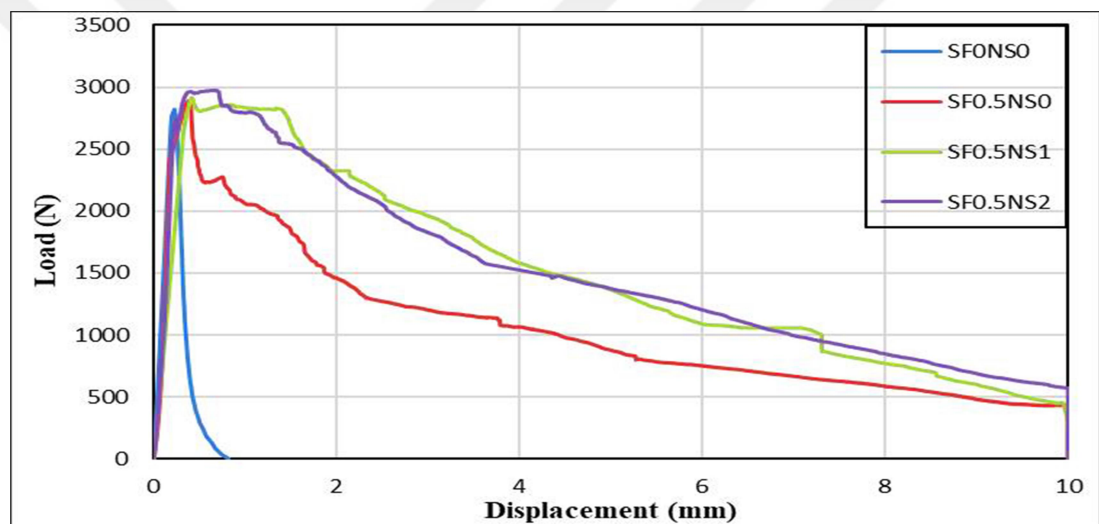
Figure 4.9 Typical failure patterns of SCGC

4.2.3 Flexural strength

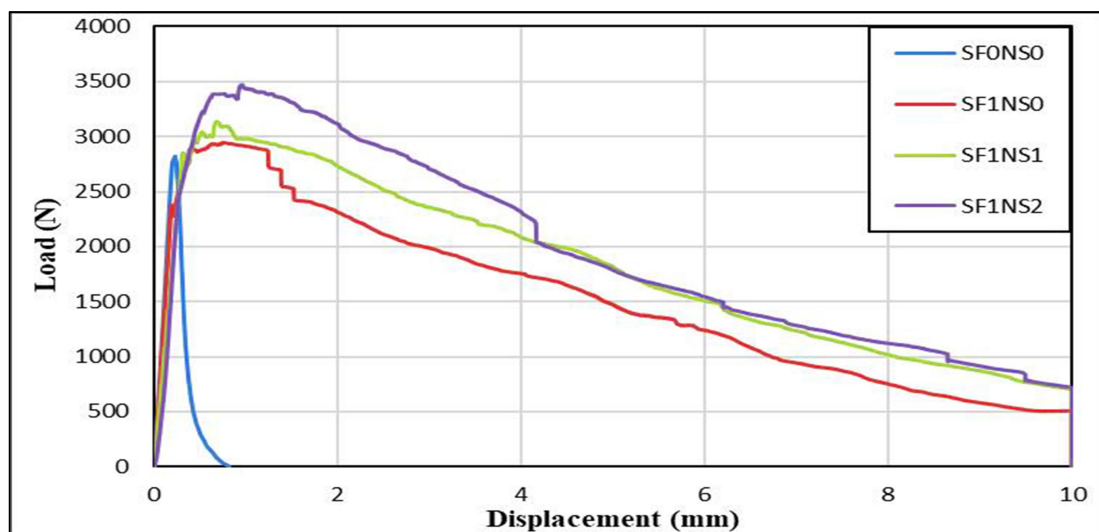
The load-displacement curves of SCGC specimens resulting from three-point bending tests are shown in Figure 4.10. Generally, GPC and OPC presented a linear behavior until the first crack occurs and strain-softening behavior was noticed for all specimens after peak load. The load-displacement curves of the non-fibrous specimens and containing NS exhibited approximately similar behavior and similar flexural strength values were found. By studying the influence of SF and the combined influence of NS and SF on flexural strength and as shown in Figure 4.11 it was noticed that the flexural strength improved with the increase in NS content under the same SF volume fraction. Moreover, the specimens with higher NS and SF presented lower load relaxations and so higher residual flexural strengths as compared to specimens without NS and SF. This result may be due to the evolution of the bond strength between the SF and the matrix when the NS is added. The combined use of NS and SF showed the best bending performance and the maximum flexural strength was measured in the specimens containing 2% NS and 1% SF.



(a) Effect of NS without SF



(b) Effect of NS with 0.5% SF



(c) Effect of NS with 1% SF

Figure 4.10 Effect of NS and SF on the load-displacement curve of SCGC

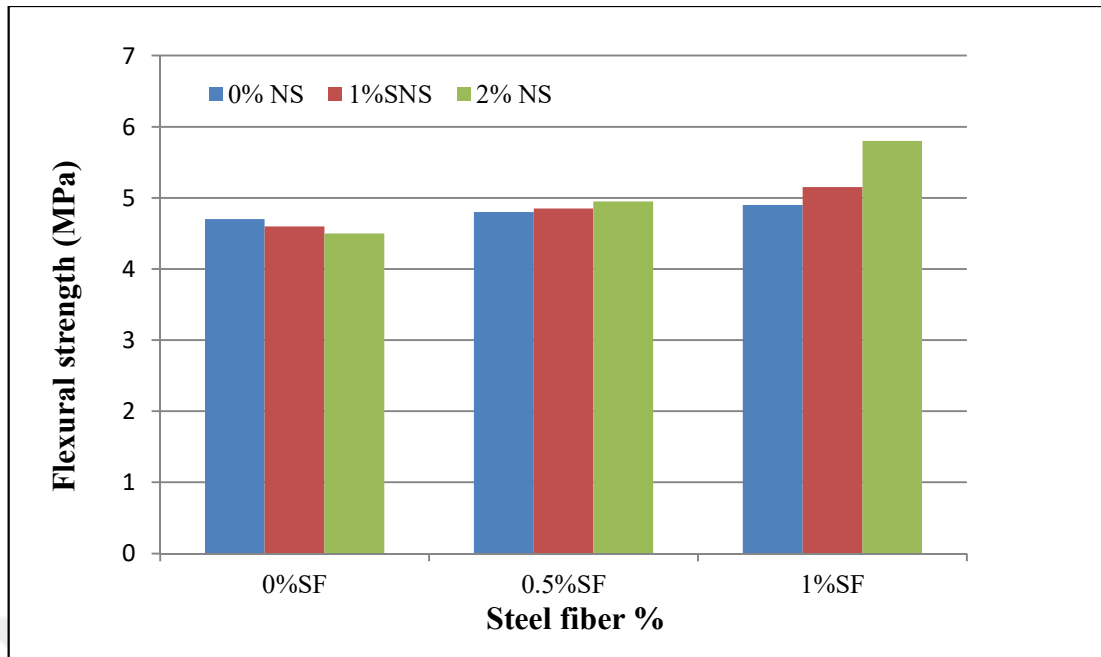


Figure 4.11 Influence of NS and SF on the flexural strength

4.3 Fracture performance

In order to calculate the area under load-displacement curve for all prismatic specimens the equation 3.4 was used. Similar fracture energy results were obtained for the specimens without SF. In the case of the combined use of NS and SF, a positive development in the fracture energy of specimens was found with an increase in the volume of NS and SF as shown in Figure 4.12. The effect of SF is attributed to its ability to close the cracks and thus to prevent them from opening up loading to further displacement in the SCGC specimens. Meanwhile, NS may increase the bond strength and increase the adhesion between SF and the geopolymer binder matrix. The combined use of NS and SF in SCGC specimens showed superior fracture performance as compared to the specimens without NS and SF. Based on the compressive strength results given in Figure 4.7, it can be concluded that higher fracture energy results are attributed to higher compressive strength of the specimens containing NS and SF.

Sarker et al. (2013) explored the fracture energy of the heat cured FA-based GPC, and they proved that the fracture energy improved with an increase of compressive strength of the specimens.

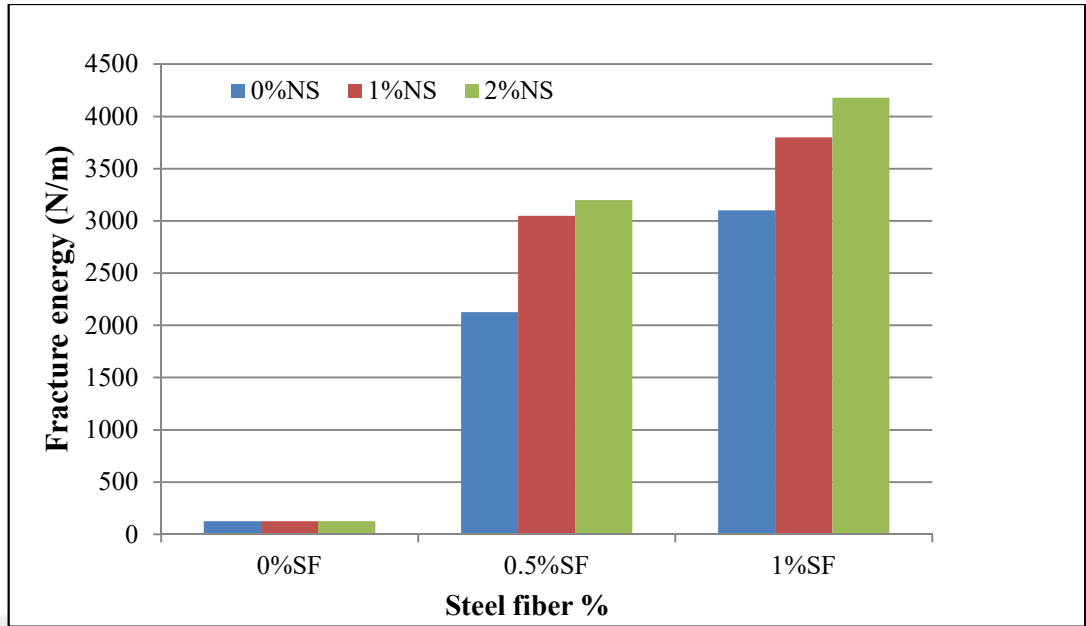


Figure 4.12 Effect of NS and SF on Fracture Energy of SCGC

The critical stress intensity factor of SCGC specimens at 28 days was measured using 3.5 equation and the results are given in Figure 4.13. K_{IC} refers to stress intensity required to propagate the crack. Similar critical stress Intensity factor results were obtained for the specimens without SF and with 0.5% and 1% SF. When SF volume fraction was increased to 1%, the K_{IC} value increased with an increase in NS amount. Therefore, more stresses were required to open the new cracks in the specimens when higher SF volume fraction (1%) and NS ratio (2%) were used. All mechanical properties of SCGC specimens are shown in Table 4.2.

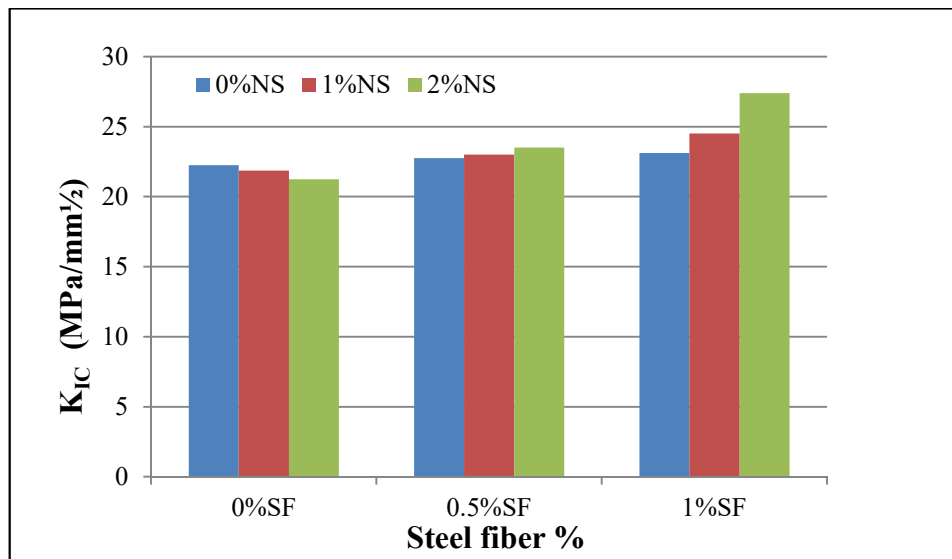


Figure 4.13 Effect of NS and SF on the stress intensity factor

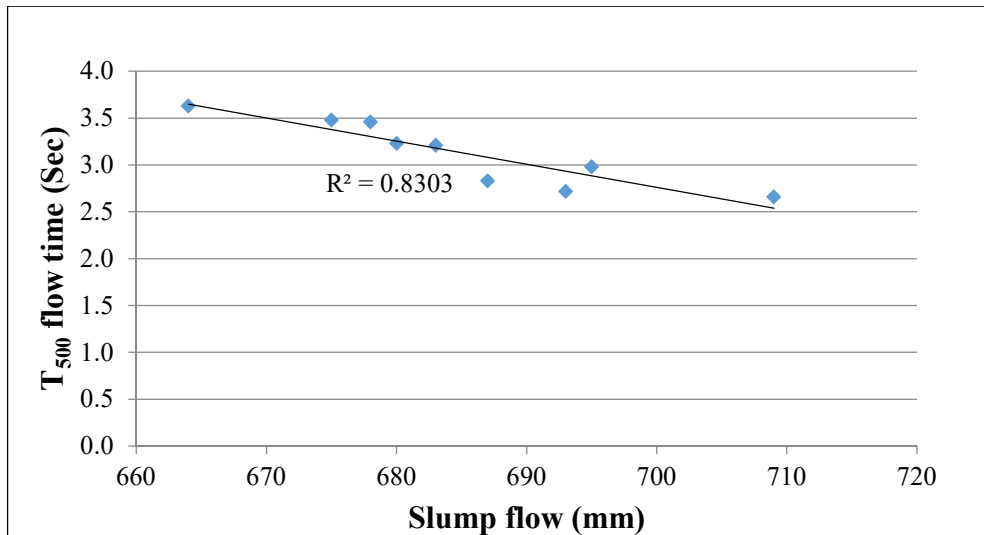
Table 4.2 The results of Fresh and hardened tests

mixtures	Fresh state test results				Hardened state test results				
	slump flow dia. (mm)	slump flow time (sec)	V-funnel flow (sec)	L-Box H2/H1	compressive strength (MPa)	bond strength (MPa)	flexural strength (MPa)	Fracture Energy (N/m)	intensity factor K_{IC} (MPa)
SF0 NS0	709	2.66	10.84	0.96	60.70	11.60	4.70	125	22.25
SF0 NS1	695	2.98	13.24	0.91	58.40	11.80	4.60	125	21.87
SF0 NS2	680	3.23	16.63	0.88	57.60	12.05	4.50	125	21.25
SF0.5 NS0	693	2.72	12.83	0.92	63.74	12.90	4.80	2125	22.75
SF0.5 NS1	683	3.21	14.90	0.89	60.10	13.40	4.85	3050	23.00
SF0.5 NS2	675	3.48	17.50	0.85	57.90	14.95	4.95	3200	23.50
SF1 NS0	687	2.83	13.76	0.90	65.55	13.20	4.90	3100	23.12
SF1 NS1	678	3.46	17.00	0.87	61.70	14.10	5.15	3800	24.50
SF1 NS2	664	3.63	18.50	0.82	59.84	14.55	5.80	4180	27.40

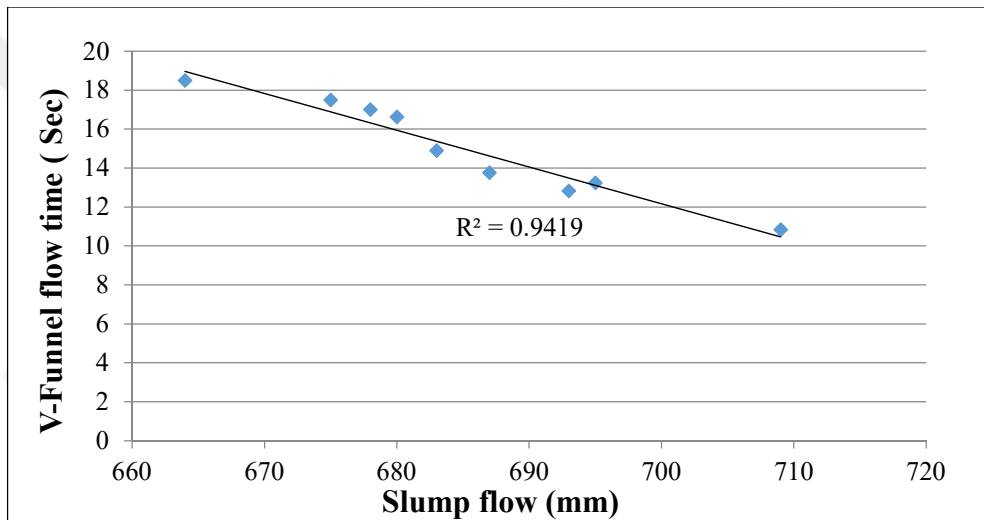
4.4 Correlation between fresh and hardened properties of SCGC

It is significant to study the correlation of experimental data to evaluate the results. Theoretically, the essential parameters that control the fresh and hardened properties of the concrete are the relative volume fractions of the cementitious binder, water/binder ratio, and aggregates. As previously mentioned, the compressive strength affects most mechanical properties of the concrete. The goal of this study is to investigate the combined effect of NS and SF on the fresh state and mechanical properties of SCGC. Hence, the influences of these parameters can also be evaluated by correlating the obtained experimental data to each other. As shown in Figure 4.14, the correlation coefficients (R^2) were calculated and given. It is observed that there are good relationships between slump flow and T_{500} time (R^2 : 0.8235), L-Box and slump flow (R^2 :0.9419), and V-funnel and slump flow (R^2 :0.9739). The high values of R^2 show that slump flow and other fresh state properties are well correlated even for the existence of NS and SF.

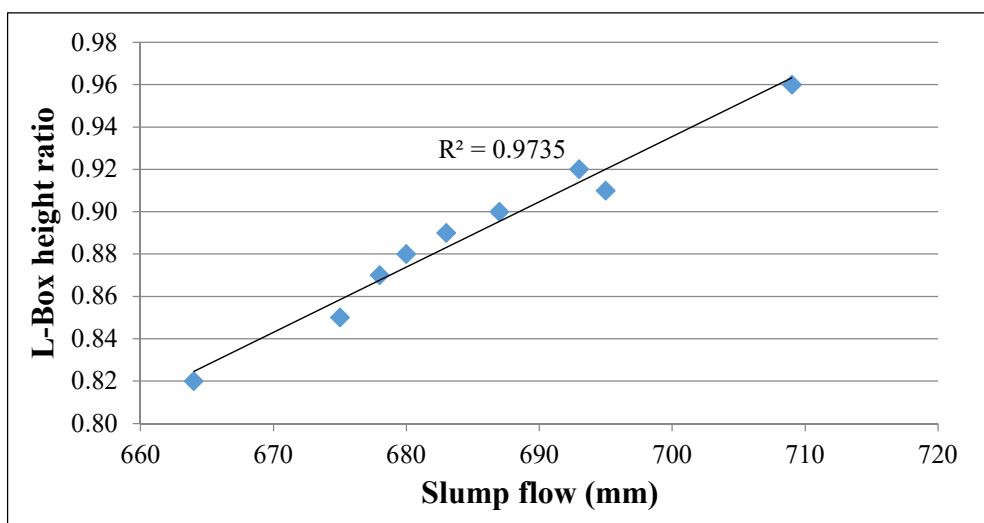
In addition, there are noticeable relationships between slump flow and compressive strength, slump flow and bond strength, and slump flow and fracture toughness as shown in Figure 4.15. The high values of R^2 exhibit that the mechanical properties of SCGC are affected from the slump flow performance of SCGC in spite of existence of NS and SF. Likewise, there are also good relationships exist between the hardened state performances of SCGC. The high coefficients of correlation are found between compressive strength and bond strength, compressive strength and flexural strength, compressive strength and fracture energy, compressive strength and critical stress intensity factor, bond strength and flexural strength, and bond strength and critical stress intensity factor, as shown in Figure 4.16. Generally, experimental results show that there are strong relationships between fresh state properties and mechanical properties performance of SCGC specimens in spite of the presence NS and SF.



(a) Slump flow vs. T_{500}

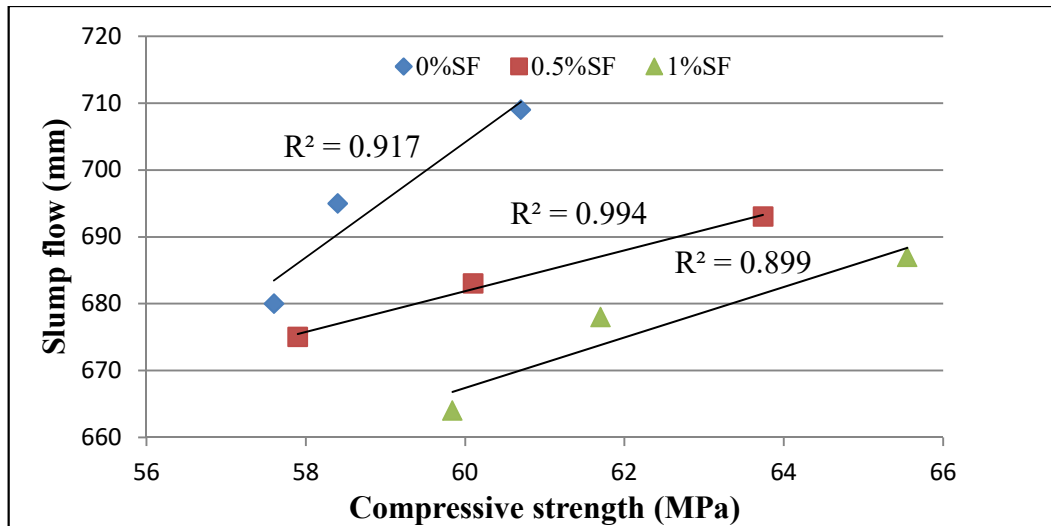


(b) Slump flow vs. V-Funnel

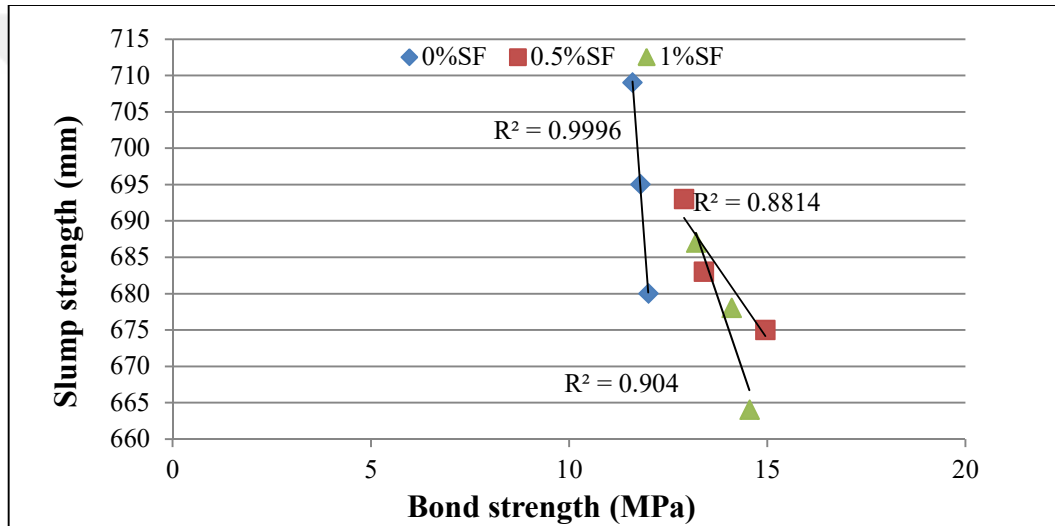


(c) Slump flow vs. L-Box

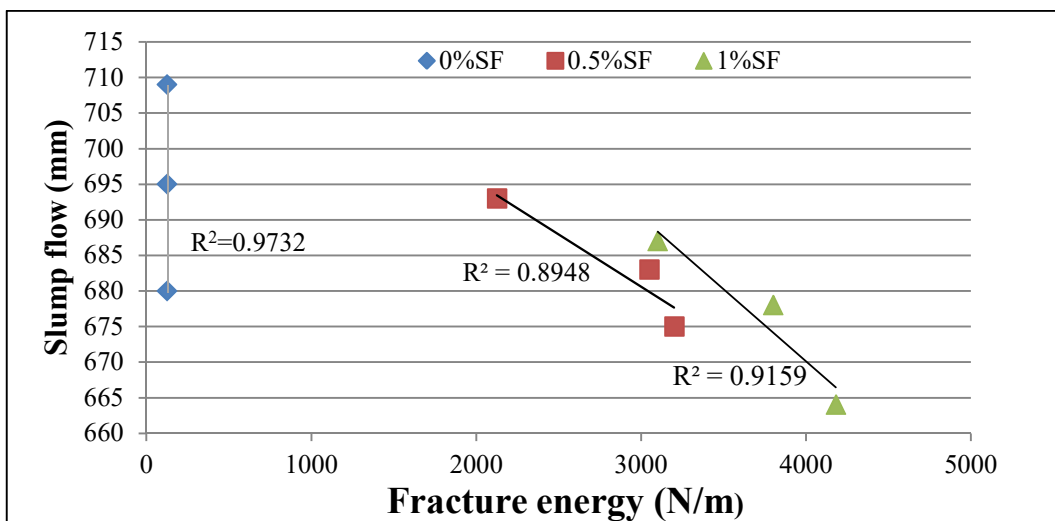
Figure 4.14 Correlation between the fresh properties of SCGC



(a) Slump flow vs. compressive strength

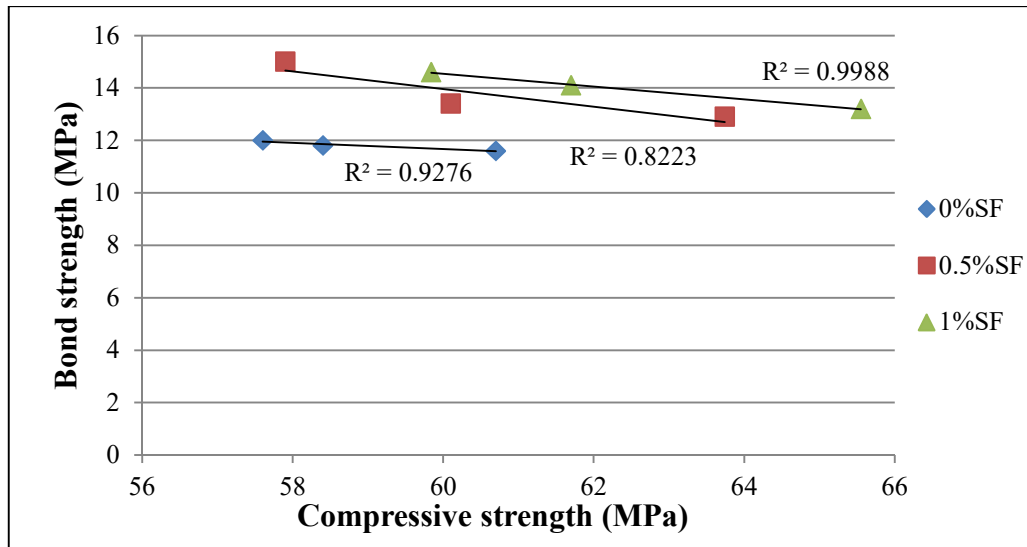


(b) Slump flow vs. bond strength

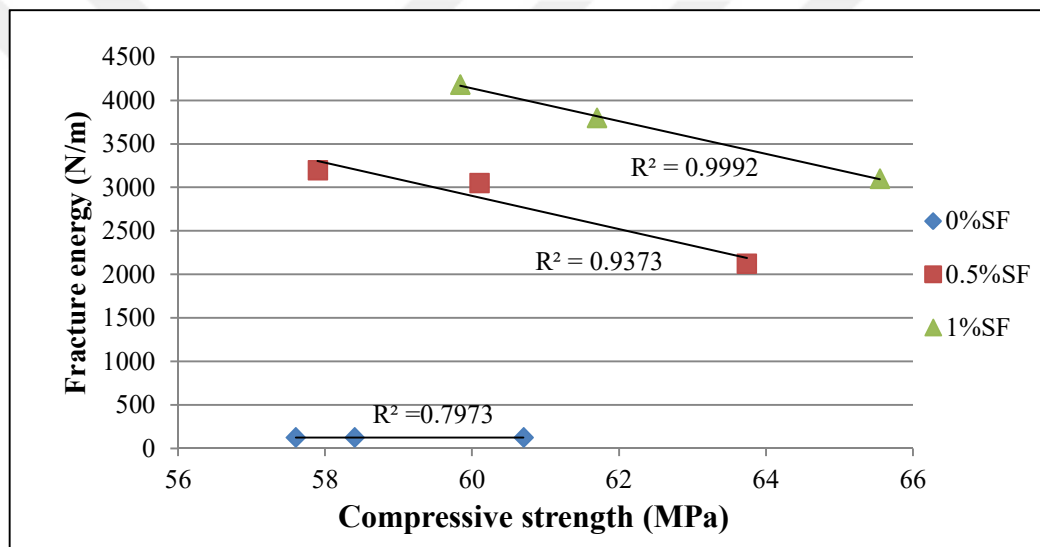


(c) Slump flow vs. fracture energy

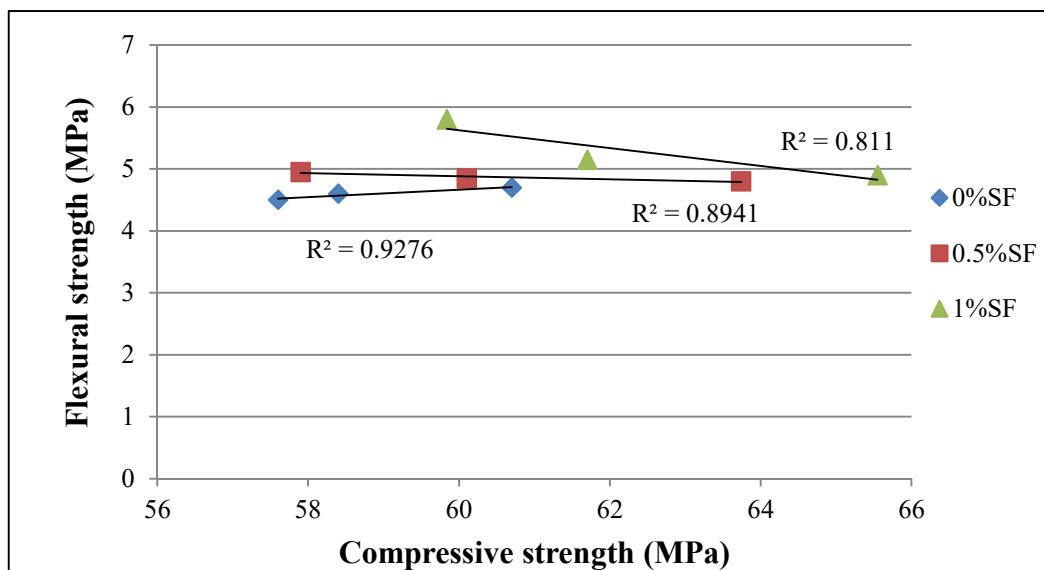
Figure 4.15 Correlation between the fresh and hardened properties of SCGC



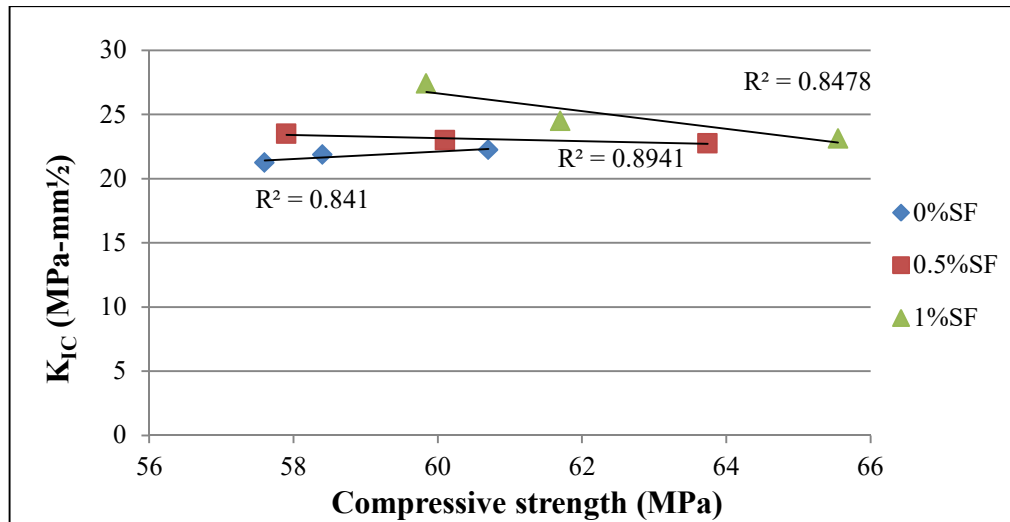
(a) Compressive strength vs. bond strength



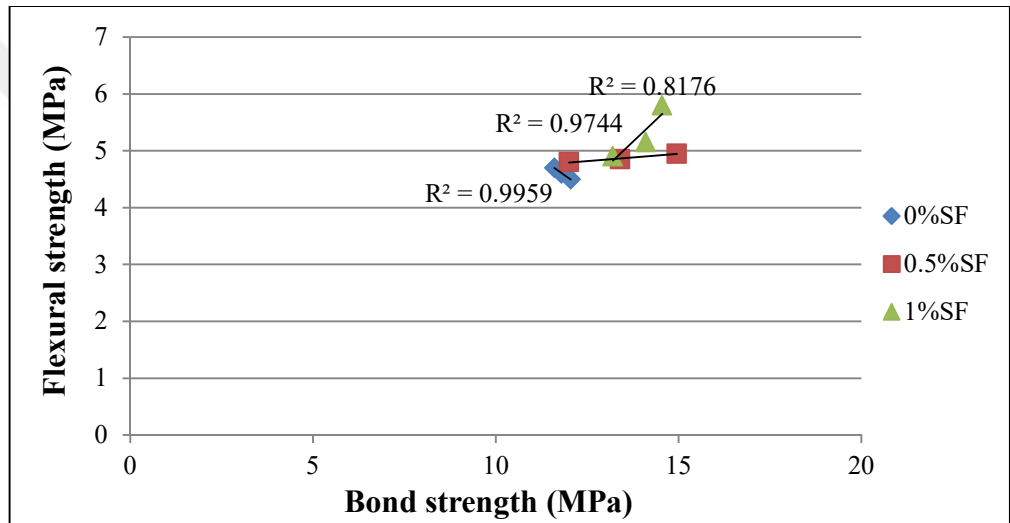
(b) Compressive strength vs. fracture energy



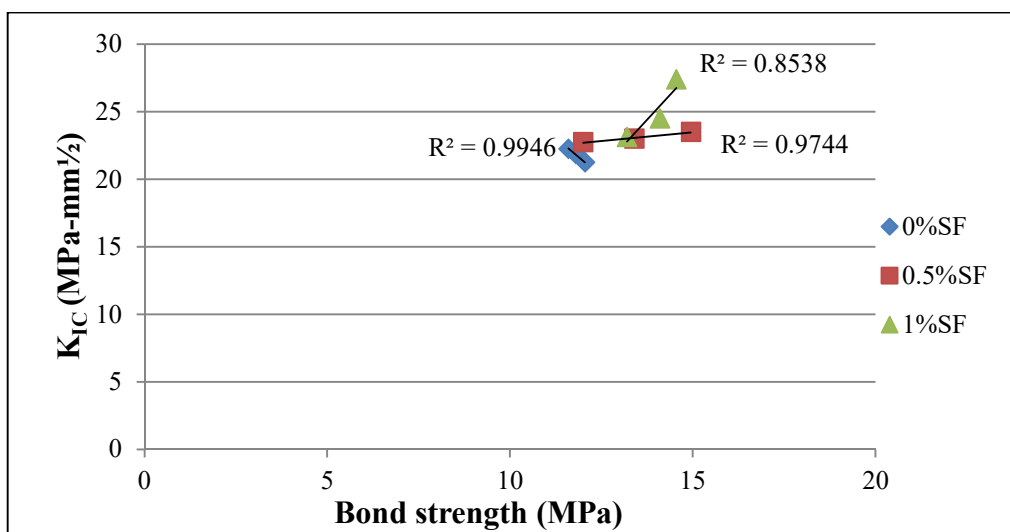
(c) Compressive strength vs. flexural strength



(d) Compressive strength vs. K_{IC}



(e) Bond strength vs. flexural strength



(f) Bond strength vs. K_{IC}

Figure 4.16 Correlation between the hardened properties of SCGC

CHAPTER 5

CONCLUSIONS

5.1 Conclusions of the study

This study presents the effects of the combined use of nano-silica and steel fiber under different percentages of NS (0 %, 1 %, and 2 %) and different percentages of SF (0 %, 0.5 %, and 1 %) on the fresh state properties and mechanical properties of fly ash/ ground granulated blast furnace slag (FA/GGBFS) based self-compacting geopolymer concrete. The experimental results were analyzed in detail and summarized as follows:

- It is observed that combined use of NS and SF decreases the slump flow, T_{500} flow time, V-funnel flow time and L-Box passing ability. The highest amount of NS (2%) and SF (1%) results the highest reduction in the fresh state performance. However, the self-compacting geopolymer mixtures have fulfilled the required flowability and passing ability criteria according to EFNARC specifications and EN 12350 standards.
- Addition of 2% nano-silica into the SCGC mixtures improves the resistance to segregation and bleeding, it is concluded that the mixtures containing NS are more cohesive than that non-containing.
- Slump flow and V-funnel results present that all SCGC mixes are in the range of VS2/VF2 viscosity category, which has good segregation and bleeding resistance, and low formwork pressure according to EFNARC standards.
- A slight reduction in compressive strength has been observed as a result of addition nano-silica to SCGC mixtures, unlike steel fiber which slightly improves the compressive strength of SCGC specimens. The decreasing influence of NS on the compressive strength has been recompensed by the presence of SF.

- Presence of steel fiber in SCGC specimens improves the flexural strength, fracture toughness, bond strength, and K_{IC} results of SCGC specimens. Although, nano-silica has no contributing effect on flexural performance, when it is used with steel fibers, meaningfully enhances bond strength, flexural strength, and fracture properties of SCGC specimens.
- The best mechanical performance is obtained for the specimens with the highest amounts of nano-silica (2%) and steel fiber (1%).
- The nano-silica addition was found to be the most dominant factor than the addition of steel fiber regarding both fresh state performances and the compressive strength of the specimens. However, the utilization of SF is observed to be the most predominant factor regarding the bond strength and flexural performances of the SCGC specimens.

5.2 Recommendation for Future Research

According to the results obtained from this research, it should be noted that the fresh state properties of self-compacting geopolymer concrete may not satisfy the EFNARC specifications, if the percentage of nano-silica and steel fiber exceeds 2% and 1%, respectively, when used together. Adding of SF up to 1.5% may lead to increase the mechanical properties of SCGC. Using 70 % of fly ash with 30% ground granulated blast furnace slag as a binder is likely to increase the compressive strength of SCGC.

REFERENCES

- Abdullah, M. M. A. B., Tahir, M. F. M., Tajudin, M. A. F. M. A., Ekaputri, J. J., Bayuaji, R., & Khatim, N. A. M. (2017, November). Study on The Geopolymer Concrete Properties Reinforced with Hooked Steel Fiber. In *IOP Conference Series: Materials Science and Engineering* (Vol. **267**, No. 1, p. 012014). IOP Publishing.
- Abu-Lebdeh, T., Hamoush, S., Heard, W., & Zornig, B. (2011). Effect of matrix strength on pullout behavior of steel fiber reinforced very-high strength concrete composites. *Construction and Building Materials*, **25(1)**, 39-46.
- ACI Committee 544. (1988). Design considerations for steel fiber reinforced concrete, ACI 544-4R. *ACI Structural Journal* 563– 578.
- Adak, D., Sarkar, M., & Mandal, S. (2014). Effect of nano-silica on strength and durability of fly ash based geopolymer mortar. *Construction and Building Materials*, **70**, 453-459.
- Adak, D., Sarkar, M., & Mandal, S. (2017). Structural performance of nano-silica modified fly-ash based geopolymer concrete. *Construction and Building Materials*, **135**, 430-439.
- Akçay, B., & Tasdemir, M. A. (2009). Optimisation of using lightweight aggregates in mitigating autogenous deformation of concrete. *Construction and Building Materials*, **23(1)**, 353-363.
- Al-Amoudi, O. S. B., Maslehuddin, M., & Abiola, T. O. (2004). Effect of type and dosage of silica fume on plastic shrinkage in concrete exposed to hot weather. *Construction and Building materials*, **18(10)**, 737-743.
- Aliabdo, A. A., Elmoaty, A. E. M. A., & Salem, H. A. (2016). Effect of water addition, plasticizer and alkaline solution constitution on fly ash based geopolymer concrete performance. *Construction and Building Materials*, **121**, 694-703.

Alyhya, W. S. (2016). Self-compacting concrete: mix proportioning, properties and its flow simulation in the V-funnel (Doctoral dissertation, Cardiff University).

Assaedi, H., Shaikh, F. U. A., & Low, I. M. (2015). Characteristics of Nanosilica-Geopolymer Nanocomposites and Mixing Effect. *Int. J. Chem*, **9(12)**, 1363-1370.

ASTM C 618. (2005). Standard Specification for Coal Fly Ash and Raw Calcined Natural Pozzolan for Use in Concrete.

Standard, A. S. T. M. (2013). C1437-13. *Test Method for Flow of Hydraulic Cement Mortar*.

ASTM C39/C39M-01, Standard test method for compressive strength of cylindrical concrete specimens, Am. Soc. Test. Mater. West Conshohocken, USA. (2003).

Aydın, S. (2013). Effects of fiber strength on fracture characteristics of normal and high strength concrete. *Periodica Polytechnica Civil Engineering*, **57(2)**, 191-200.

Aydın, S., & Baradan, B. (2013). The effect of fiber properties on high performance alkali-activated slag/silica fume mortars. *Composites Part B: Engineering*, **45(1)**, 63-69.

Balaguru, P. N., & Shah, S. P. (1992). *Fiber-reinforced cement composites*.

Balaguru, P., Narahari, R., & Patel, M. (1992). Flexural toughness of steel fiber reinforced concrete. *Materials Journal*, **89(6)**, 541-546.

Baran, E., Akis, T., & Yesilmen, S. (2012). Pull-out behavior of prestressing strands in steel fiber reinforced concrete. *Construction and Building Materials*, **28(1)**, 362-371.

Behbahani, H. P., Nematollahi, B., & Farasatpour, M. (2013). Steel fiber reinforced concrete: A review.

Beigi, M. H., Berenjian, J., Omran, O. L., Nik, A. S., & Nikbin, I. M. (2013). An experimental survey on combined effects of fibers and nanosilica on the mechanical, rheological, and durability properties of self-compacting concrete. *Materials & Design*, **50**, 1019-1029.

- Belkowitz, J. S., Belkowitz, W. B., Nawrocki, K., & Fisher, F. T. (2015). Impact of Nanosilica Size and Surface Area on Concrete Properties. *ACI Materials Journal*, **112**(3).
- Bentur, A., & Mindess, S. (2014). *Fibre reinforced cementitious composites*. CRC Press.
- Bentur, A., & Mindess, S.(1990). *Fibre reinforced cementitious composites*. NewYork: Elsevier Applied Science.
- Bernal, S., De Gutierrez, R., Delvasto, S., & Rodriguez, E. (2010). Performance of an alkali-activated slag concrete reinforced with steel fibers. *Construction and building Materials*, **24**(2), 208-214.
- Bernal, S., Mejía de Gutiérrez, R., Rodríguez, E., & Delvasto, S. (2006, November). Performance of geopolymeric concrete reinforced with steel fibers. *In 10th Int. Bonded Inorganic Bonded Fiber Composites Conference. Proceedings IIBCC. Sao Pablo-Brasil* (pp. 156-167).
- Bouguermouh, K., Bouzidi, N., Mahtout, L., Pérez-Villarejo, L., & Martínez-Cartas, M. L. (2017). Effect of acid attack on microstructure and composition of metakaolin-based geopolymers: The role of alkaline activator. *Journal of Non-Crystalline Solids*, **463**, 128-137.
- BS EN, 12350-10. (2010). Testing Self Compacting Concrete: L-Box Test, Br. Stand. Int.
- BS EN, 12350-9 (2010). Testing Self Compacting Concrete.V-Funnel Test, Br. Stand. Int.
- BS EN. 12350-8. (2010). Testing Self Compacting Concrete. Slump Flow Test. Br. Stand. Int.
- Castel, A., & Foster, S. J. (2015). Bond strength between blended slag and Class F fly ash geopolymer concrete with steel reinforcement. *Cement and Concrete Research*, **72**, 48-53.

- Çevik, A., Alzeebaree, R., Humur, G., Niş, A., & Gülşan, M. E. (2018). Effect of nano-silica on the chemical durability and mechanical performance of fly ash based geopolymer concrete. *Ceramics International*, **44(11)**, 12253-12264.
- Chen, C., Habert, G., Bouzidi, Y., & Jullien, A. (2010). Environmental impact of cement production: detail of the different processes and cement plant variability evaluation. *Journal of Cleaner Production*, **18(5)**, 478-485.
- Cwirzen, A. (2010). Controlling physical properties of cementitious matrixes by nanomaterials. In *Advanced Materials Research* (Vol. **123**, pp. 639-642). Trans Tech Publications.
- Dahake, A. G., & Charkha, K. S. (2016). Effect of Steel Fibers on Strength of Concrete.
- Davidovits, J. (1993). Geopolymer cements to minimise carbon-dioxide greenhouse-warming. *Ceram. Trans.*, **37**, 165-182.
- Davidovits, J. (1994). Global warming impact on the cement and aggregates industries. *World Resource Review*, **6(2)**, 263-278.
- Davidovits, J. (2002, October). Environmentally driven geopolymer cement applications. In *Proceedings of 2002 Geopolymer Conference. Melbourne. Australia*.
- Davidovits, J. (2008). *Geopolymer chemistry and applications*. Geopolymer Institute.
- Davidovits, J. (2015). False values on CO₂ emission for geopolymer cement/concrete published in scientific papers. *Technical Paper*, **24**.
- Deb, P. S., Nath, P., & Sarker, P. K. (2014). The effects of ground granulated blast-furnace slag blending with fly ash and activator content on the workability and strength properties of geopolymer concrete cured at ambient temperature. *Materials & Design* (1980-2015), **62**, 32-39.
- Deb, P. S., Sarker, P. K., & Barbhuiya, S. (2015). Effects of nano-silica on the strength development of geopolymer cured at room temperature. *Construction and Building Materials*, **101**, 675-683.

Deepa Raj, S., Abraham, R., Ganesan, N., & Sasi, D. (2013). Fracture properties of fibre reinforced geopolymer concrete. *Int J Sci Eng Res*, **4(5)**, 75-80.

Dias, D. P., & Thaumaturgo, C. (2005). Fracture toughness of geopolymeric concretes reinforced with basalt fibers. *Cement and concrete composites*, **27(1)**, 49-54.

Ding, Y., & Bai, Y. L. (2018). Fracture Properties and Softening Curves of Steel Fiber-Reinforced Slag-Based Geopolymer Mortar and Concrete. *Materials*, **11(8)**, 1445.

Doguparti, R. S. (2015). A study on bond strength of geopolymer concrete. *International Journal of Civil Environmental, Structural, Construction and Architectural Engineering*, **9(3)**, 355-358.

Duxson, P., Provis, J. L., Lukey, G. C., & Van Deventer, J. S. (2007). The role of inorganic polymer technology in the development of 'green concrete'. *Cement and Concrete Research*, **37(12)**, 1590-1597.

EFNARC, S. (2002). Guidelines for Self-Compacting Concrete, European Federation for Specialist Construction Chemicals and Concrete Systems, Norfolk, UK. *English ed., February*.

EFNARC, S. (2002). Guidelines for self-compacting concrete. *London, UK: Association House*, **32, 34**.

EFNARC.(2005). The European guidelines for self-compacting concrete specification, production and use. *Self-compacting concrete*.

Elboghdadi, A. S., Elkady, H. M., Salem, H. M., & Farahat, A. M. (2015). Effect of Nano Silica and Steel Fiber on Properties of Concrete. *International Journal of Modern Trends in Engineering and Research*, **2(7)**, 207-217.

El-Didamony, H., Amer, A. A., & Ela-ziz, H. A. (2012). Properties and durability of alkali-activated slag pastes immersed in sea water. *Ceramics International*, **38(5)**, 3773-3780.

Fallah, S., & Nematzadeh, M. (2017). Mechanical properties and durability of high-strength concrete containing macro-polymeric and polypropylene fibers with nano-silica and silica fume. *Construction and Building Materials*, **132**, 170-187.

Farhan, N. A., Sheikh, M. N., & Hadi, M. N. (2018). Engineering Properties of Ambient Cured Alkali-Activated Fly Ash–Slag Concrete Reinforced with Different Types of Steel Fiber. *Journal of Materials in Civil Engineering*, **30(7)**, 04018142.

Farhan, N. A., Sheikh, M. N., & Hadi, M. N. (2018, August). Behaviour of Ambient Cured Steel Fibre Reinforced Geopolymer Concrete Columns Under Axial and Flexural Loads. In *Structures* (Vol. **15**, pp. 184-195). Elsevier.

Gambhir ML. (1986). *Concrete technology*. New Delhi: McGraw Hill Publishing.

Ganesan, N., Indira, P. V., & Santhakumar, A. (2013). Engineering properties of steel fibre reinforced geopolymer concrete. *Advances in concrete construction*, **1(4)**, 305-318.

Gao, X., Yu, Q. L., & Brouwers, H. J. H. (2015). Characterization of alkali activated slag–fly ash blends containing nano-silica. *Construction and Building Materials*, **98**, 397-406.

Gencel, O., Brostow, W., Datashvili, T., & Thedford, M. (2011). Workability and mechanical performance of steel fiber-reinforced self-compacting concrete with fly ash. *Composite interfaces*, **18(2)**, 169-184.

Gopalaratnam, V. S., & Shah, S. P. (1987). Tensile failure of steel fiber-reinforced mortar. *Journal of Engineering Mechanics*, **113(5)**, 635-652.

Gopinath, S., Mouli, P. C., Murthy, A. R., Iyer, N. R., & Maheswaran, S. (2012). Effect of nano silica on mechanical properties and durability of normal strength concrete. *Archives of Civil Engineering*, **58(4)**, 433-444.

Gorgis, I. N., Hassan, M. S., & Abdulkareem, R. T. (2016). Effect of Steel Fibers, Polypropylene Fibers and/or Nanosilica on Mechanical Properties of Self-Consolidating Concrete. *Engineering and Technology Journal*, **34(3 Part (A) Engineering)**, 527-538.

Green, B. H. (2008). Development of a high-density cementitious rock-matching grout using nano-particles. *Special Publication*, **254**, 121-132.

Guerrero, P., & Naaman, A. E. (2000). Effect of mortar fineness and adhesive agents on pullout response of steel fibers. *Materials Journal*, **97(1)**, 12-20.

Gunasekara, C., Law, D. W., Setunge, S., & Sanjayan, J. G. (2015). Zeta potential, gel formation and compressive strength of low calcium fly ash geopolymers. *Construction and building materials*, **95**, 592-599.

Güneyisi, E., Gesoğlu, M., Mohamadameen, A., Alzebaree, R., Algin, Z., & Mermerdaş, K. (2014). Enhancement of shrinkage behavior of lightweight aggregate concretes by shrinkage reducing admixture and fiber reinforcement. *Construction and Building Materials*, **54**, 91-98.

Harajli, M. H., & Salloukh, K. A. (1997). Effect of fibers on development/splice strength of reinforcing bars in tension. *Materials Journal*, **94(4)**, 317-324.

Hardjito, D., Wallah, S. E., Sumajouw, D. M., & Rangan, B. V. (2004). Factors influencing the compressive strength of fly ash-based geopolymer concrete. *civil engineering dimension*, **6(2)**, 88-93..

Hasanbeigi, A., Menke, C., & Price, L. (2010). The CO₂ abatement cost curve for the Thailand cement industry. *Journal of Cleaner Production*, **18(15)**, 1509-1518.

Ibrahim, K. I. M. (2017). The Effect of Fibers Type and Content on Nano Silica Concrete [Nsc].

Ji, T. (2005). Preliminary study on the water permeability and microstructure of concrete incorporating nano-SiO₂. *Cement and Concrete Research*, **35(10)**, 1943-1947.

Khale, D., & Chaudhary, R. (2007). Mechanism of geopolymerization and factors influencing its development: a review. *Journal of materials science*, **42(3)**, 729-746.

Komljenović, M., Bašćarević, Z., & Bradić, V. (2010). Mechanical and microstructural properties of alkali-activated fly ash geopolymers. *Journal of Hazardous Materials*, **181(1-3)**, 35-42.

- Krstulovic-Opara, N., Watson, K. A., & LaFave, J. M. (1994). Effect of increased tensile strength and toughness on reinforcing-bar bond behavior. *Cement and Concrete Composites*, **16**(2), 129-141.
- Li, H., Xiao, H. G., Yuan, J., & Ou, J. (2004). Microstructure of cement mortar with nano-particles. *Composites Part B: Engineering*, **35**(2), 185-189.
- Li, V. C. (1998). Engineered cementitious composites-tailored composites through micromechanical modeling.
- Li, Z. (2011). *Advanced concrete technology*. John Wiley & Sons.
- Mahadik, S. A., Kamane, S. K., & Lande, A. C. (2014). Effect of Steel Fibers on Compressive and Flexural Strength of Concrete. *International Journal of Advanced Structures and Geotechnical Engineering*, **3**(04), 388-392.
- Malhotra, V. M. (2002). Introduction: sustainable development and concrete technology. *Concrete International*, **24**(7).
- Memon, F. A., Nuruddin, M. F., Khan, S., Shafiq, N. A. S. I. R., & Ayub, T. (2013). Effect of sodium hydroxide concentration on fresh properties and compressive strength of self-compacting geopolymer concrete. *Journal of Engineering Science and Technology*, **8**(1), 44-56.
- Naik, T. R. (2005, July). Sustainability of cement and concrete industries. *In Proceedings of the international conference global construction: ultimate concrete opportunities, Dundee, Scotland* (pp. 141-150).
- Naskar, S., & Chakraborty, A. K. (2016). Effect of nano materials in geopolymer concrete. *Perspectives in science*, **8**, 273-275.
- Nazari, A., & Riahi, S. (2011). The effects of SiO₂ nanoparticles on physical and mechanical properties of high strength compacting concrete, *Composites Part B, Engineering*, **42**(3), 570-578.
- Nematollahi, B., & Sanjayan, J. (2014). Effect of different superplasticizers and activator combinations on workability and strength of fly ash based geopolymer. *Materials & Design*, **57**, 667-672.

Nuruddin, F., Demie, S., Memon, F. A., & Shafiq, N. (2011). Effect of superplasticizer and NaOH molarity on workability, compressive strength and microstructure properties of self-compacting geopolymer concrete. *World Academy of Science, Engineering and Technology*, **75**.

Nuruddin, F., Shafiq, N., & Qazi, S. (2010). Compressive strength & microstructure of polymeric concrete incorporating fly ash & silica fume. *Journal of the Canadian Society of Civil Engineering*.

Okamura, H., & Ouchi, M. (2003). Self-compacting concrete. *Journal of advanced concrete technology*, **1(1)**, 5-15.

Olivia, M., & Nikraz, H. (2012). Properties of fly ash geopolymer concrete designed by Taguchi method. *Materials & Design (1980-2015)*, **36**, 191-198.

Pacheco-Torgal, F., Moura, D., Ding, Y., & Jalali, S. (2011). Composition, strength and workability of alkali-activated metakaolin based mortars. *Construction and Building Materials*, **25(9)**, 3732-3745.

Peng, G. F., Yang, W. W., Zhao, J., Liu, Y. F., Bian, S. H., & Zhao, L. H. (2006). Explosive spalling and residual mechanical properties of fiber-toughened high-performance concrete subjected to high temperatures. *Cement and Concrete Research*, **36(4)**, 723-727.

Peterson, P. E. (1980). Fracture energy of concrete: Method of determination. *Cement and Concrete research*, **10(1)**, 79-89.

Phoo-ngernkham, T., Chindaprasirt, P., Sata, V., Hanjitsuwan, S., & Hatanaka, S. (2014). The effect of adding nano-SiO₂ and nano-Al₂O₃ on properties of high calcium fly ash geopolymer cured at ambient temperature. *Materials & Design*, **55**, 58-65.

Qing, Y. E., Zenan, Z., Li, S., & Rongshen, C. (2006). A comparative study on the pozzolanic activity between nano-SiO₂ and silica fume. *Journal of Wuhan University of Technology-Mater. Sci. Ed.*, **21(3)**, 153-157.

Qing, Y., Zenan, Z., Deyu, K., & Rongshen, C. (2007). Influence of nano-SiO₂ addition on properties of hardened cement paste as compared with silica fume. *Construction and building materials*, **21**(3), 539-545.

Raijiwala, D. B., & Patil, H. S. (2011). Geopolymer concrete: A concrete of the next decade. *Concrete Solutions* 2011, **287**.

Ramkumar, G., Sundarkumar, S., & Sivakumar, A. (2015). Development of steel fibre reinforced geopolymer concrete. *International Journal of Advance Research in Science and Engineering*, **4**(1), 1717-1725.

Ranjbar, N., Talebian, S., Mehrali, M., Kuenzel, C., Metselaar, H. S. C., & Jumaat, M. Z. (2016). Mechanisms of interfacial bond in steel and polypropylene fiber reinforced geopolymer composites. *Composites Science and Technology*, **122**, 73-81.

Recommendation, R. D. (1985). Determination of the fracture energy of mortar and concrete by means of three-point bend tests on notched beams. *Materials and structures*, **18**(106), 285-290.

Recommendation, R. D. (1985). Determination of the fracture energy of mortar and concrete by means of three-point bend tests on notched beams. *Materials and structures*, **18**(106), 285-290.

Reddy, K. M., & Kumar, G. N. (2017). Experimental study on Self Compacting Geopolymer Concrete.

Reis, J. M. L. (2006). Fracture and flexural characterization of natural fiber-reinforced polymer concrete. *Construction and building materials*, **20**(9), 673-678.

Reis, J. M. L. (2007). Fracture toughness of fiber reinforced polymer concrete. *Mechanics of Solids in Brazil*.

Rilem, T. C. (1994). RILEM recommendations for the testing and use of constructions materials. *RC*, **6**, 218220.

Said, A. M., & Zeidan, M. S. (2009). Enhancing the reactivity of normal and fly ash concrete using colloidal nano-silica, *Special Publication*, **267**, 75-86.

Sarker, P. (2010). Bond strengths of geopolymer and cement concretes. *In Advances in Science and Technology* (Vol. **69**, pp. 143-151). Trans Tech Publications.

Sarker, P. K., Haque, R., & Ramgolam, K. V. (2013). Fracture behaviour of heat cured fly ash based geopolymer concrete. *Materials & Design*, **44**, 580-586.

Sayyad, A. S., & Patankar, S. V. (2013). Effect of steel fibres and low calcium fly ash on mechanical and elastic properties of geopolymer concrete composites. *Indian Journal of Materials Science*, 2013.

Schneider, M., Romer, M., Tschudin, M., & Bolio, H. (2011). Sustainable cement production—present and future. *Cement and Concrete Research*, **41(7)**, 642-650.

Scrivener, K. L., & Young, J. F. (2014). *Mechanisms of chemical degradation of cement-based systems*. CRC Press.

Serag, M. I., Yasien, A. M., El-Feky, M. S., & Elkady, H. (2017). Effect of nano silica on concrete bond strength modes of failure. *International Journal*, **12(29)**, 2892-2899.

Shaikh, F. U. A. (2013). Deflection hardening behaviour of short fibre reinforced fly ash based geopolymer composites. *Materials & Design*, **50**, 674-682.

Shih, J. Y., Chang, T. P., & Hsiao, T. C. (2006). Effect of nanosilica on characterization of Portland cement composite. *Materials Science and Engineering: A*, **424(1-2)**, 266-274.

Silica Fume Association. (2005). *Silica fume manual*, 38860 Sierra Lane, Lovettsville, VA 20180, USA

Sivakumar, A., & Srinivasan, K. (2014). High performance fibre reinforced alkali activated slag concrete. *International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering*, **8**, **12**.

Škvára, F., Jílek, T., & Kopecký, L. (2005). Geopolymer materials based on fly ash. *Ceram.-Silik*, **49(3)**, 195-204.

Song, P. S., & Hwang, S. (2004). Mechanical properties of high-strength steel fiber-reinforced concrete. *Construction and Building Materials*, **18**(9), 669-673.

Soufeiani, L., Raman, S. N., Jumaat, M. Z. B., Alengaram, U. J., Ghadyani, G., & Mendis, P. (2016). Influences of the volume fraction and shape of steel fibers on fiber-reinforced concrete subjected to dynamic loading—A review. *Engineering Structures*, **124**, 405-417.

Sunilkumar S.P. & Amol A.P. 2015. *International Journal of Research in Advent Technology*, Vol. **3**, pp.

Tavakoli, H. R., Omran, O. L., Shiade, M. F., & Kutanaei, S. S. (2014). Prediction of combined effects of fibers and nanosilica on the mechanical properties of self-compacting concrete using artificial neural network. *Latin American Journal of Solids and Structures*, **11**(11), 1906-1923.

Taylor, H. F. W. (1994). Sulfate reactions in concrete--microstructural and chemical aspects. *Ceramic Transactions*, **40** pp. 61.

Their, J. M., & Özakça, M. (2018). Developing geopolymer concrete by using cold-bonded fly ash aggregate, nano-silica, and steel fiber. *Construction and Building Materials*, **180**, 12-22.

US Research Nanomaterials, Inc (2015). Silicon Oxide Nanoparticles Certificate of Analysis, Silicon Oxide Nanopowder/SiO₂ Nanoparticles 2015.

Vairagade, V. S., & Kene, K. S. (2013). Strength of normal concrete using metallic and synthetic fibers. *Procedia Engineering*, **51**, 132-140.

Van Chanh, N., Trung, B. D., & Van Tuan, D. (2008, November). Recent research geopolymer concrete. *In The 3rd ACF International Conference-ACF/VCA, Vietnam* (Vol. **18**, pp. 235-241).

Vijai, K., Kumutha, R., & Vishnuram, B. G. (2010). Effect of types of curing on strength of geopolymer concrete. *International journal of physical sciences*, **5**(9), 1419-1423.

Wafa, F. F., & Ashour, S. A. (1992). Mechanical properties of high-strength fiber reinforced concrete. *Materials Journal*, **89**(5), 449-455.

Wallah, S., & Rangan, B. V. (2006). Low-calcium fly ash-based geopolymer concrete: long-term properties.

Wang, Y., Chen, J., Gao, D., & Huang, E. (2018). Mechanical Properties of Steel Fibers and Nanosilica Modified Crumb Rubber Concrete. *Advances in Civil Engineering*, 2018.

Wardhono, A., Law, D. W., Sutikno, & Dani, H. (2017, September). The effect of slag addition on strength development of Class C fly ash geopolymer concrete at normal temperature. In *AIP Conference Proceedings* (Vol. **1887**, No. 1, p. 020030). AIP Publishing.

Yang, Z., Weiss, W. J., & Olek, J. (2004). Interaction between micro-cracking, cracking, and reduced durability of concrete: developing methods for considering cumulative damage in life-cycle modeling.

Yazıcı, Ş., İnan, G., & Tabak, V. (2007). Effect of aspect ratio and volume fraction of steel fiber on the mechanical properties of SFRC. *Construction and Building Materials*, **21**(6), 1250-1253.

Yuvaraj, S., & Srinivasan, K. (2016). Performance of Geopolymer Concrete using Varying Sizes of Steel Fibres. *Indian Journal of Science and Technology*, **9**(37).

Zhang, P., Zhao, Y. N., Li, Q. F., Wang, P., & Zhang, T. H. (2014). Flexural toughness of steel fiber reinforced high performance concrete containing nano-SiO₂ and fly ash. *The Scientific World Journal*, 2014.