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M.Sc. in Civil Engineering

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STRUCTURAL BEHAVIOR OF GEOPOLYMER CONCRETE BEAMS

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Structural Behavior of Geopolymer Concrete Beams

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Supervisor
Prof. Dr. Mustafa ÖZAKÇA

By
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ABSTRACT

STRUCTURAL BEHAVIOR OF GEOPOLYMER CONCRETE BEAMS

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M.Sc. in Civil Engineering

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In this study, the effects of steel fiber and polypropylene fiber on the flexural performance of fiber-reinforced geopolymer were investigated. Fiber reinforcement has emerged as a way to improve the brittleness of geopolymer. This study aims to examine the performance of fly ash/slag-based geopolymer concrete (FA/GGBFS) with different concentration of sodium hydroxide (NaOH) and different types of fibers (steel and polypropylene fibers). Alkaline liquid consists of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) solutions. The ratio of sodium silicate solution to sodium hydroxide was fixed to 2.50. The main factors studied were the evaluation of workability, compressive strength, split tensile strength, critical stress intensity factor, and fracture toughness. The study results showed that the incorporation of steel and polypropylene fibers into fly ash/slag based geopolymer concrete resulted in superior enhancement in the splitting tensile strength, flexural strength, area under the load-deflection curve and in the degree of fracture energy however the using of the different molar concentration of sodium hydroxide observed to be less important in the behavior of fiber reinforced geopolymer concrete.

Keywords: Geopolymer concrete, fly ash, slag, steel fiber, polypropylene fiber and fracture toughness.

ÖZET

GEOPOLIMER BETON ILE URETILMIS KIRISLERIN YAPISAL DAVRANISI

NAJM, Mustafa Saab

Yüksek Lisans Tezi, Insaat Mühendisliği

Tez Yöneticisi: Prof. Dr. Mustafa ÖZAKÇA

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71 sayfa

Bu çalışmada, çelik lif ve polipropilen elyaf takviyesinin geopolimer betonun eğilme performansına etkileri araştırılmıştır. Elyaf takviyesi, geopolimer betonun kırılganlığını iyileştirmenin bir yolu olarak ortaya çıkmaktır. Bu çalışmada, farklı konsantrasyonlarda sodyum hidroksit (NaOH) ve farklı lif türleri (çelik ve polipropilen lifler) ile uçucu kül/ cüruf kullanIlarak Üretilen geopolimer betonun (FA/GGBFS) performansının incelenmesi amaçlanmıştır. Alkali sıvı, sodyum hidroksit (NaOH) ve sodyum silikat (Na_2SiO_3) çözeltilerinden oluşmaktadır. Sodyum silikat çözeltisinin sodyum hidroksite oranı 2.50 olarak sabitlenmiştir. Çalışılan ana faktörler işlenebilirlik, basınç dayanımı, yarmada çekme mukavemeti, kritik stres yoğunluğu faktörü ve kırılma tokluğunun değerlendirilmesidir. Çalışma sonuçları, çelik ve polipropilen liflerin uçucu kül/ cüruf esaslı geopolimer betona dahil edilmesinin, yarmada çekme gerilme mukavemeti, eğilme mukavemeti, yük sapma eğrisi altındaki alan ve kırılma enerjisi derecesinde üstün bir artışla sonuçlandığını göstermiştir. Farklı molar konsantrasyonlarda sodyum hidroksitin elyaf takviyeli geopolimer betonun davranışında daha az önemli olduğu gözlemlenmiştir.

Anahtar Kelimeler: Geopolimer beton, uçucu kül, cüruf, çelik lif, polipropilen elyaf ve kırılma tokluğu

To My Parents

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I am ever grateful to ALLAH, the Creator and the Guardian, and to whom I owe my very existence.

All thanks and gratitude to my dear family for their faith and support during my academic study.

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LIST OF SYMBOLS/ ABBREVIATIONS

GPC	Geopolymer concrete
FA	Fly ash
GGBFS	Ground granulated blast furnace slag
OPC	Ordinary Portland cement
SF	Steel fiber
PPF	Polypropylene fiber
NaOH	Sodium hydroxide
Na_2SiO_3	Sodium silicate
Al	Aluminum
Si	Silicon
ASTM	American society for testing and materials
LOI	Loss of ignition
SP	Super-plasticizer
$f_c^{'}$	Compressive strength
f_s	Splitting tensile strength
G_F	Fracture energy
f_{flex}	Net flexural strength
K_{IC}	Critical stress intensity factor
CEB-FIP	CEB-FIP committee equation
LVDT	Linear variable displacement transducer

CHAPTER 1

INTRODUCTION

1.1 General

With growing demand on Ordinary Portland Cement (OPC) industries to decrease their greenhouse gas. It has become necessary to find alternative binders to OPC because the manufacture of cement generates an approximately equal quantity of greenhouse gases and that cement production is considered responsible for (7- 8%) of all greenhouse gas emissions released worldwide. For this, the investigation of alternative materials has increased. Nowadays, different kinds of waste are utilized as additives to conventional concrete in order to develop its mechanical strength, durability and fracture energy [1].

Geopolymer concrete (GPC) is considered as a new form of concrete materials which has recently been grown as a future concrete used by product materials like slag, Fly Ash (FA), silica fume, etc. instead of cement. Geopolymer besides to its eco-friendly characteristic, demonstrate several superior properties like a heat resistance, a good resistance to chemical attacks, high early strength, low shrinkage, and low creep. The mechanism of GPC represented by strong alumina-silicate (Al-SiO_2) polymeric structures involves generation of alumina and silica by sodium or potassium hydroxides (KOH) and sodium silicates (Na_2SiO_3) as alkaline liquid [2]. The main elements of GPC are the alkali-activated solution and the source materials. The quantity of silicon and aluminum should be high in alumina-silicate based source materials to create a reaction between the alkali-activated solution and the source material. The selection of source materials to produce GPC depends on many elements like cost, type of application and availability.

The existence of calcium (Ca) compound in the geopolymer source material like FA and Ground Granulated Blast Furnace Slag (GGBFS) play a significant role since the calcium ion is able to act as a charge balancing cation in the geopolymer binder. Low calcium FA has been investigated to be an appropriate binder for GPC production and can utilize as an effective OPC replacement because of its availability, low cost reduced water demand and useful alumina and silica –due to composition [3].

The alkali-activated solution consists of soluble alkali metals which are mostly potassium (K) or sodium (Na) based. The incorporation of (potassium or sodium) hydroxide with (potassium or sodium) silicate is the most common alkali-activated solution utilized in geopolymerization. The kind and the molarity of the alkali-activated solution play a central role in the binder of the GGBFS or FA. The solubility of aluminum and silica ions in sodium hydroxide (NaOH) solubility is higher than in potassium hydroxide (KOH) liquid [4]. Therefore, NaOH has an essential role in the compressive strength and the structure of the GPC. Increasing the molar concentration of NaOH in GPC appears to improve the compressive strength together with a substantial influence on the short-term strength cured at 60 °C for 48 h [4]. Silicon, aluminum and other minor ions initiate to dissolve when the GGBFS or FA come into contact with NaOH. The amount of dissolution depends on the concentration of NaOH and dissolution time [5].

Most of the researchers conducted on FA / slag based GPC was about the molar concentration, the change of strength for GPC with a different temperature of curing range between (45°C – 80 °C) for about (2–3) h, and mix proportion. However, a few types of researchers reported the effect of fibers on fresh and mechanical properties of GPC. Fibers are mostly utilized in concrete to control cracking based on plastic and drying shrinkages also the addition of fibers in concrete enhance the mixture to decrease the permeability of concrete by diminishing bleeding water.

The main reason for inclusion fibers in concrete is to develop its post-cracking ductility, tensile strength, and flexural strength. In addition that unreinforced GPC is still brittle with very low tensile and flexural strengths like conventional concrete and the addition fibers to the mixture to overcome this deficiency. Various kinds of fibers are utilized to reinforce the concrete. Among many fibers, steel fibers offered a significant enhancement in the tensile and flexural strength, toughness and ductility

of GPC. The inclusion Steel Fiber (SF) in GPC showed outstanding mechanical properties at elevated temperature as compared with conventional concrete [6].

1.2 Application of Geopolymer Concrete

1.2.1 Precast geopolymer concrete

High-short-strength gain is a property of GPC when cured in stem or heat cured, though ambient room temperature curing is possible for GPC. It has been utilized to produce precast beams, panels, walls, sewer pipes and railway sleepers (see Figure 1.1). The early-age strength of GPC gains is distinguishing that can best be used in the precast concrete where heat or steam curing is common practice and is utilized to increase the rate of manufacture of elements.

Figure 1.1 Precast FA/GGBFS based GPC floors parts

1.2.2 Pavement

The utilize of GPC in pavement shows a clear difference to conventional concrete because the GPC had low bleeding and the quantity of water rising to the surface is very small as compared with conventional concrete as shown Figure 1.2. To preserve suitable surface moisture for floating, screeding and troweling operations as well as offer protection in opposition to drying, an aliphatic alcohol due to surface spray were utilized throughout the full placement time [7].

Figure 1.2 Road pavements by GPC

1.2.3 Retaining wall

A total of over 40 MPa GPC precast panels were utilized as retaining wall for design a private house. The geopolymer panels were up to six meters long by 2.4 meters extensive and were designed to retain the ground pressure of three meters. The precast GPC panels were cast in Toowoomba and cured under ambient conditions before being sent to site for installation as shown in Figure 1.3.

Figure 1.3 Precast GPC retaining walls for a private house

1.3 Objectives of Research

The main objectives of this study are:

- Investigation of the influence of molarity on short and long-term properties of GPC.
- Investigation of the effect of fibers on the mechanical properties of GPC.
- Estimation of the relationships between compressive and tensile strength, fracture energy, flexural strength and fracture toughness.

1.4 Arrangement of Thesis

Chapter one: This chapter contains a brief introduction about geopolymer, the aims of research and the significance of research as well as a brief introduction to molar concentration and fiber reinforced GPC.

Chapter two: In this chapter was discussion the previous researches related to the GPC, alternative material and the influence of the molarity and kinds of fibers on the mechanical properties and the durability of GPC.

Chapter three: This chapter contains all details related to the experimental program like materials, mixing, curing and test procedure.

Chapters four: In this chapter, the results of the test have been presented and discussed.

Chapter five: This chapter conducted the conclusions of the study.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

GPC can play an important role in the context of sustainability and environmental issues. The manufacturing of OPC responsible for 7% of global carbon dioxide (CO_2) emissions and the large uses of cement are poses threat to the living organism day by day. The manufacture of 1 tone of OPC releases approximately 1 tone of CO_2 to the atmosphere [8].

The using of alternative materials throughout of the world quickly increasing with the growth of the industrial sector, especially in China and India. Last decades, the application of GPC becomes an important part of the research. The total worldwide production of FA in 2011-2012 was approximately 780 Mt. Though effective utilization of FA was limited to 53% of total production and usually different from country to another [9]. The production of alternative materials reduces the greenhouse from 80% to 90% less than cement. Therefore a full replacement of cement with FA or GGBFS would considerably diminish the CO_2 emission of concrete production [10].

In another hand, alternative materials like FA and GGBFS may be activated by utilizing alkali-activated liquids to form a binder and hence partial or total replacement of OPC in concrete by the alternative materials. The alkalinity of the alkali-activated can be high to medium or low. In the first case, the important contents to activate the GPC are silicon and calcium in the by-product material like FA or GGBFS. The main binder formed is a Calcium silicate hydrate gel, as the result of a hydration process.

2.2 Mechanism of Geopolymer Concrete

The mechanism of GPC mostly depends on many variables like the molar concentration of the alkali activator, curing regime, the water content and the mineralogical and the chemical composition of the binder material. The stages of the mechanism or geopolymerisation process of GPC as shown below:

1. The first step is the dissolution of the alumina and silica ions which based source materials within the amorphous phase of the binder material. The process is motivated by the alkali-activated liquid during initial mixing [11]. As seen in Figure 2.1.
2. The reaction between the neighboring alumina and silica molecules as known condensation which takes place in the liquid. The alkali activated based GPC also behaves as a catalyst during this phase. This reaction causes the neighboring hydroxyl ions to create an oxygen bond which links a water molecule and the molecules.
3. The final step is named poly-condense, which leads to form an interlocking network of oxygen bonded tetrahedrally.

2.3 Constituent of Geopolymer Concrete

2.3.1 Fly ash

The term of FA can be defined based on ASTM [13] “The finely separated residue that generated from the process of combustion of powdered coal or ground and that is transferred by flue gasses”. FA is usually manufactured by the steam generating plants and coal-fired electric as shown in Figure 2.2.

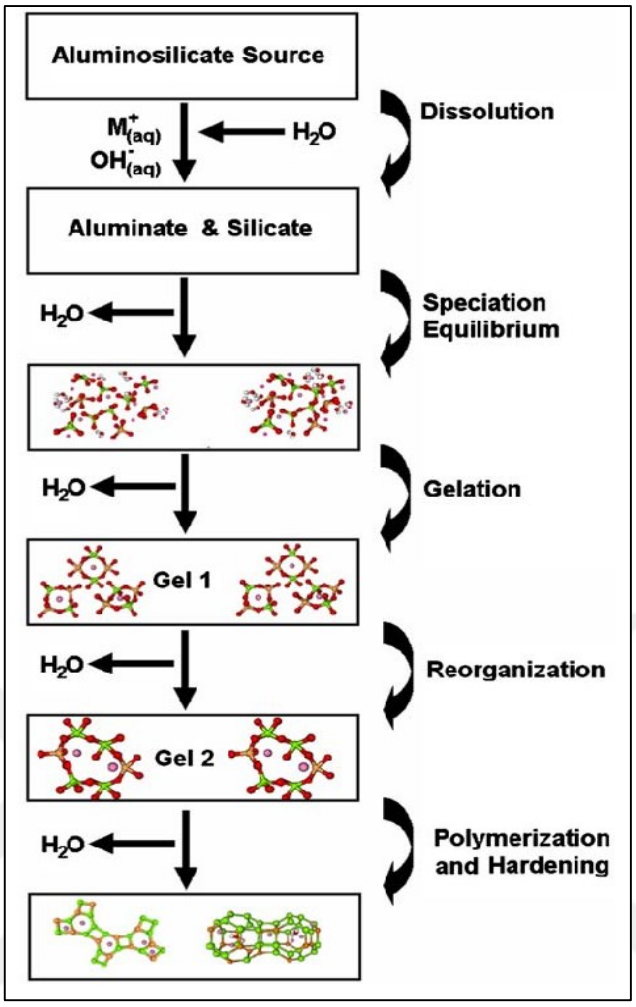


Figure 2.1 Geopolymerization process [12]

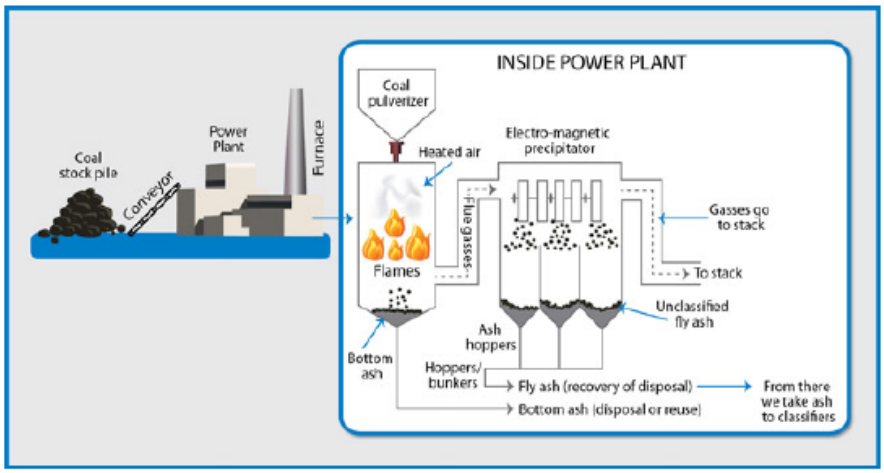


Figure 2.2 The process of manufacturing of FA in a power plant [14]

FA particles are naturally spherical, finer than lime OPC, the diameter of particles ranging from less than 1 μm to no more than 150 μm (Figure 2.3). ASTM 618-12

[15] specified two major classes of FA depending on chemical conformation resulting from the kind of coal burned; The two kinds of FA named class C and F. Class F is FA usually manufactured from bituminous coal or burning anthracite, and FA class C is generally formed from the burning of sub-bituminous coal and lignite [16]. The difference between class F and C is the quantity of silica, calcium, alumina, and the amount of iron in FA. The quantity of calcium in class F FA is less than 20%. While class C FA has higher calcium content (20-40 mass %) than class F. The influence of high CaO generally helps to increase the rate of reaction.

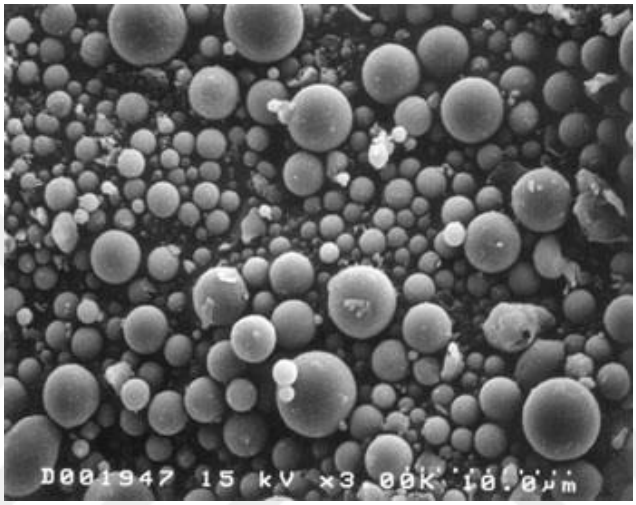


Figure 2.3 FA particles enlargement [17]

2.3.1.1 Use of fly ash in concrete

The spherical shape of FA often supports to develop the workability of the fresh concrete, whereas the small particles size of FA plays a significant role as a filler of voids in the mixture, and make dense and durable concrete. The use of FA can enhance a lot of properties in concrete such as better workability, durability, ultimate strength and cohesiveness. In additional that, the fine particles in FA can lead to diminishing segregation and bleeding in concrete which helps to develop the final properties, particularly in lean mixes.

Usage of FA in concrete can be useful to decrease the permeability of concrete to water and aggressive agents. A significant achievement in utilize of FA in OPC concrete is the improvement of high volume FA that successfully substitutes utilize of OPC in concrete up to 60% and yet has excellent mechanical properties with improved durability performance. High volume FA based concrete has been showed

to be more resource-efficient and durable than the conventional concrete [18]. The High volume fly ash technology has been placed into practice, for example, the construction of ways in India, which implemented 50% OPC replacement by the High volume fly ash.

2.3.2 Slag

Slag or GGBFS is a by-product of the generating of iron in a blast-furnace where limestone, coke, and iron ore are heated at 1500°C. Two kinds of products generating from the high heating, the first product is molten iron and the second is molten slag. The molten slag floats on the top of the molten iron because it's lighter than molten iron. This molten slag consists of generally silicates and alumina, incorporated with some oxides from the limestone. Quick quenching GGBFS forms granular particles, prevents the formation of crystal lattices [19].

Small particles dominate GGBFS in alkali-activated systems and cement mixture. The particles larger than 20 μm commonly interact slowly, whilst particles smaller than 2 μm interact fully during 24 hr. Consequently, when the GGBFS is utilized in Geopolymerization, accurate control of the particle size should be ensured to control the strength of the bonds [20].

2.3.2.1 Use of slag in concrete

It is well known that utilizing GGBFS in OPC concrete as a replacement of OPC in ambient temperatures lead to strength enhancements at a lower rate as compared cement based concrete [21]. This degree of decline because of a number of variables such as slag activity the proportioning method furthermore the content of the slag in the mixture [22]. Replacing OPC with slag results in various benefits such as better workability of the fresh concrete and reducing life-cycle costs [23]. Moreover, the using GGBFS instead of OPC includes resistance against chemicals attack, temperature and gives higher compressive, split tensile and flexural strength [24]. Many previous studies reported the properties of GGBFS as a binder, they utilized sodium silicate (Na_2SiO_3) as activator binder and tested the carbonation, compressive, and flexural strength of the mortars. Thus they suggested that the mortars made by 100 % alkali activated GGBFS as a binder presented better properties than the mixed ones [25]. Previous studies also stated that the GGBFS can

be activated with alkali solutions such as water glass, sodium carbonate, and NaOH. The hydration of the alkali-activated GGBFS is closely similar to the hydration process of OPC and, in the end, hydration products similar to Calcium silicate hydrate are formed [26].

2.3.3 Alkali activator

The alkali activated liquid is one of the main factors affecting the strength improvement of GPC mixture. Generally, the combination Na_2SiO_3 with NaOH is the most utilized as solution binder because they are revealed to be the most suitable binder in terms of availability, mechanical properties and good durability [27]–[29]. NaOH Solution is generally utilized for dissolution of Si^{4+} and Al^{3+} ions from precursor materials to form alumina silicate material. Whereas Na_2SiO_3 comprises of soluble silicate species and thus is utilized to develop the condensation process of GP [30].

The usage of alkaline activated depends on various factors like cost of the solution and the reactivity required. The disintegration operation of aluminum and silica, obtainable in FA (Figure 2.4). Previous studies have been concluded that NaOH blended with Na_2SiO_3, considered to be an effective binder, yielding promising harden properties as it develops the reaction between the alkaline activated liquid and the binder [31]. Palomo et al. explained that the kind of alkaline activated used for activating GGBFS or FA significantly affects the reaction development. Moreover, they stated that high average reaction happens when an alkaline liquid activator solution contains silicate, potassium or Na_2SiO_3, in comparison to using only single alkaline hydroxides [32].

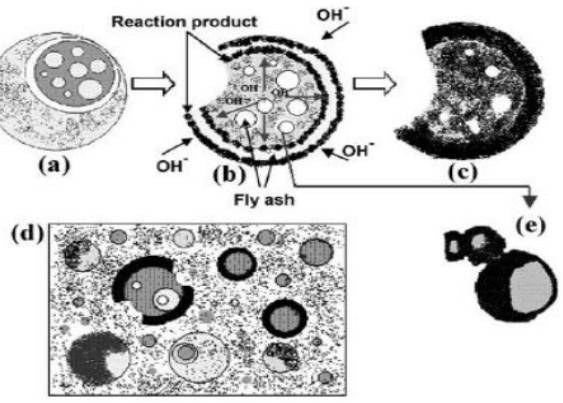


Figure 2.4 Adjective model of the alkali activation of FA [33]

2.4 Factors Affecting of Geopolymer Concrete

2.4.1 Concentration of sodium hydroxide

The concentration of NaOH is the most significant indicator for geopolymer mixture and the solubility of alumina-silicate develop with an increase in NaOH concentration. The increase in the molarity of NaOH leads to accelerating chemical dissolution, it minimized ettringite and CH formation during reaction [34]. The high molarity of NaOH solution leads to result in a high compressive strength of GPC.

Hardjito et al. [12] showed study on the influence of NaOH concentration on the compressive strength of FAGP mortar. Hardjito has stated that alkaline concentration was proportional to the compressive strength of GP mortar. Also, the authors investigated that the increase in molar concentration result in to increase the compressive strength of GP mortar [35]. Hongling Wang et al. [36], in their paper they investigated the mechanical properties and synthesis of metakaolin-based GPC have reported that higher concentration of NaOH solution provides better dissolving ability to metakaolin and make more reactive bond for the monomer. They **h**ave discovered that mechanical properties of the metakaoln-based geopolymer activating metakaoln with NaOH and Na_2SiO_3 solution were greatly dependent on the molarity of the NAOH solution. With the increase in concentrationof NaOH, the compressive, flexural strength, and apparent density of the resulting GP were increased as presented in Figure 2.5.

Subhash V. Patankar [37] reported the influence of the concentration of NaOH solution on compressive strength of GP mortar cured in an oven at 40, 60, 90, and 120 °C for the period of 24 hr and tested after three days of heat cured for the alkaline activator to FA ratio of 0.35. It is detected that the compressive strength of GPC improves with a rise in the molar concentration of NaOH solution for all temperatures nevertheless the rate of increase of strength is different by the different molarity of NaOH. The rate of increase of strength is higher at 40 and 60 °C as compared to 60 to 90 °C and 90 to 120 °C for all concentrations of NaOH. Nonetheless, there is no important variation in compressive strength of GP mortar at and above 13.11 M concentration of NaOH. It is due to a very viscous mixture formation at higher concentration of NaOH which makes compaction problem. It is also detected that the mild concentration of NaOH of 2.91M gives low strength.

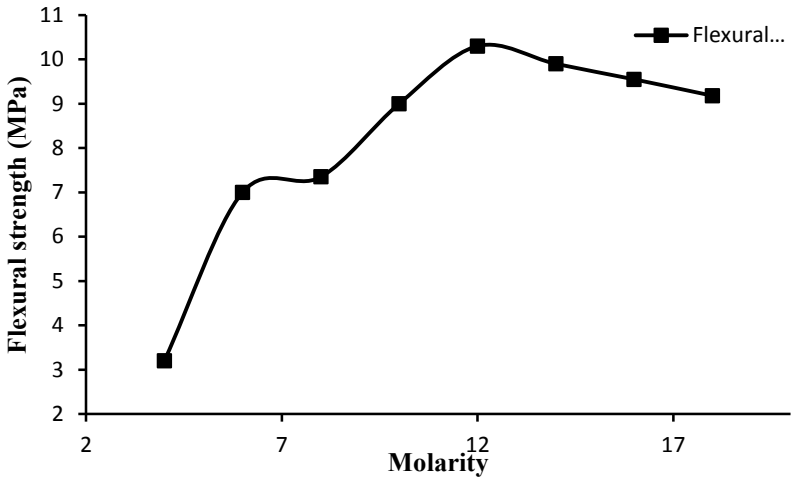


Figure 2.5 The influence of molarity of NaOH on flexural strength of GPC

The Na_2SiO_3 to NaOH ratio and the SiO_2 / Na_2O ratio considered another indicators effect on the durability and mechanical properties of GPC. The increase in the mass ratio of Na_2SiO_3 to NaOH liquid leads to enhance the compressive strength of GPC (Figure 2.6). The adding of Na_2SiO_3 to the mix design enhance harden properties of GPC beyond the ability of a hydroxide activator alone.

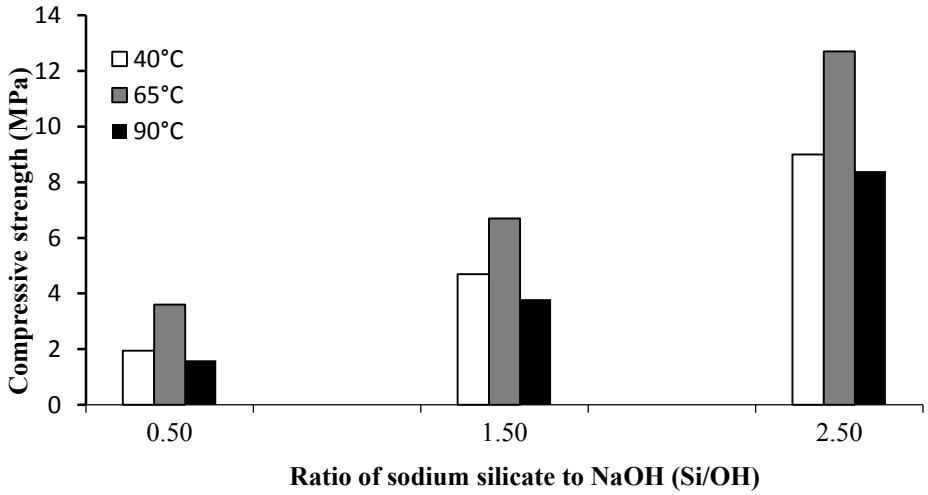


Figure 2.6 Effect of Na_2SiO_3 to NaOH ratio on the compressive strength of GPC [38]

2.4.2 Heat and curing time

A challenge for successful GPC manufacture can be found by the appropriate balancing of time and heat curing. Like OPC, the GP reaction is more simply accomplished with the adding of an outer heat source to support alkali reactivity of

the pozzolanic material. The increase in the heat curing resulted in to develop the compressive strength of GPC. Furthermore, long curing period augmented the strength of alkali-activated, nevertheless the achievement occurred at a much slower rate as time advanced due to alkaline saturation and product densification. The previous research showed that longer curing time improved the polymerization process caused higher compressive strength [39]. Heat curing significantly improves the chemical reaction that happens in the geopolymer paste. Both time and heat curing effected by the mechanical properties of GPC. Curing temperature can be done by either dry or steam curing. The results of previous researchers presented that the dry cured GPC increasing the compressive strength approximately 15% higher than that of steam-cured GPC [39]. P. Rovnaník [40] suggested that the increase in temperature up to 90 °C improves the compressive strength of the GPC (Figure 2.7). J. June *et al* [41] investigated that the increase in curing time improved the polymerization process which leads to developing the compressive strength. The noticeable increase in compressive strength was up to 24 hours of curing time Therefore, the curing time (rest period) suggested not exceed than 24 hours in practical applications.

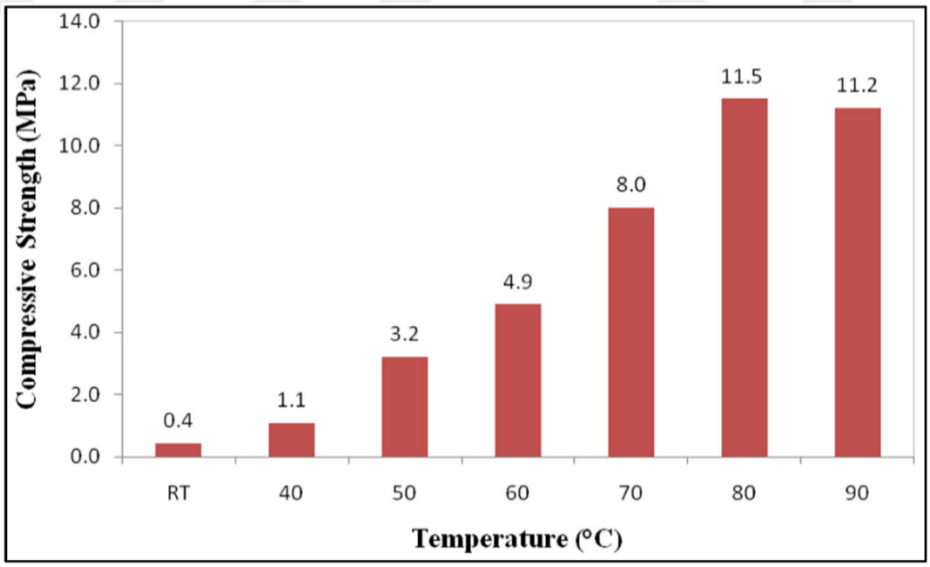


Figure 2.7 The influence of temperature on the compressive strength of GPC [42]

2.4.3 Chemical attack

GPC has a good resistance to chemical attacks such as sulfuric acid, sulfate attack, and seawater more than OPC concrete, and alkaline nature of OPC is vulnerable to

chemicals attack. Recently, alkali-activated turn into a promising alternative for highly durable concretes due to their high resistance to aggressive environments, which was already demonstrated for sulfuric acid, acetic acid, and Sulfate. Davidovits et al. stated that conventional concrete shows weight losses between (78%, and 95%) [43]. For the same conditions, he also states mass losses of (6% and 7%) for GPC exposed to 5% of sulfuric acids and hydrochloric for 28 days. A high resistance to chemicals attack is resulted due to a high alkali concentration and the existence of Ca in the binder which reduces the rate of mass transfer within the pore structures of the alkali binders [44].

2.4.4 Shrinkage

Shrinkage is a concern in OPC concrete structures because shrinkage causes cracks, and axial deformation which could make important deflection and the shrinkage prompts tension and resulting cracks moreover shrinkage if not controlled, can help to decrease durability, serviceability and even shear strength failure [45].

Shrinkage can be divided into four kinds drying, chemical, plastic and thermal shrinkage. Drying shrinkage is the diminution in the volume of concrete with time. It generally quantity for the biggest proportion of the total long-term shrinkage. The factors affecting on dry shrinkage are water-cement content, type of aggregate, maximum size, relative humidity and the size and shape of the member. Chemical shrinkage is resulting from several chemical reactions in the OPC, including the hydration shrinkage. Plastic shrinkage occurs when the concrete is still in the plastic state due to reducing of water by evaporation. Plastic shrinkage depends on various factors such as cement and water content in the mixture, temperature, ambient relative humidity and wind velocity. While thermal shrinkage is related to the quantity of heat which liberated during the hydration of cement and water. Previous research has stated that drying shrinkage is a direct result of hydration heat and rises with the increased dosage of Na_2SiO_3 activators [46]. Furthermore, it is stated that Heat-cured FAGPC undergoes to very low drying shrinkage [47].

2.5 Use of Fibers in Concrete

The most important property of concrete is its compressive strength. The tensile resistance is considerably less because of the brittleness of the material. An unreinforced conventional concrete structure has a restricted elastic response and once this elastic limit has been reached, microcracks after that macro cracks occur and finally failure. Nevertheless, the overcoming for this problem has been done by adding steel reinforcement. The reinforcing steel improves the tensile resistance and the ductility of conventional concrete.

Fibers can be divided into two types: micro and macro fibers.

2.5.1 Types of fibers

- Steel
- Synthetic
- Glass
- Natural fibers

2.5.1.1 Steel fiber

SF is generally utilized to improve the toughness of concrete by developing the impact resistance and the load-bearing capacity. The SF are formed in different sizes and shapes, due to the properties required [50]. These SF were firstly utilized as minor reinforcement or for crack control in less critical areas of the concrete elements, nonetheless currently it is extensively utilized as chief reinforcement in precast elements, shotcrete, and industrial floor slabs. The tensile resistance, provided by the SF linking a crack, will depend on the number of fibers embedded over a crack plane. Consequently, it is necessary to have a suitable quantity of fibers in the design mix. Another significant aspect that has to be into contemplation is the tensile strength of the fibers, as rupture must be avoided. The fiber's rupturing will help to a quick loss of load carrying capacity. SF naturally have no impact on the compressive strength of concrete and will only enhance the tensile strength. A study by Bernal et al. [51] was shown on alkali-activated slag concrete with the adding of SF. The results presented that GPC had a lower decrease in compressive strength compared to that of cement based concrete when SF was added. The flexural toughness was increased when higher volume fibers were added. The durability performance, like permeable porous amount and water absorption, developed meaningfully with the addition of fibers. The harden performance of the reinforced GPC even displayed similar results to that of Fiber reinforced concrete.

2.5.1.2 Polypropylene fibers

Polypropylene fibers (PPF) have been utilized to RC from the 1960's. PPF is generally formed by an extrusion process in which the polymer is hot drawn through a die until the favorite diameter is reached and chopped in different lengths as required [52]. The PPF is a synthetic hydrocarbon polymer and it is a hydrophobic material. This leads to shortcomings like low melting point, a relatively low modulus

of elasticity and weak bond characteristics with a cement matrix. The specific gravity of PPF varies from 0.9 to 0.91. The tensile strength is between (138-690) MPa and the elastic modulus varies between (3-5) GPa [52].

2.5.1.3 Microfibers

The role of microfibers (MF) is, conventionally, to decrease plastic shrinkage cracks during the curing time of OPC concrete. The adding of MF in concrete results in a material that can display high toughness and can bear a major quantity of damage in tension [48]. This result is accomplished when the fibers are linking the cracks that form. The strain hardening conduct and the small crack widths lead to obtaining a low water and chloride permeability. The length of the MF ranging from (5-30) mm and have a diameter of less than 0.1 mm. the adding excessive quantity of fibers leads to reduction the workability of the fresh concrete. Naturally, 0.1% fibers, by volume of the concrete, are added to a matrix [49].

Other benefits that MF afford when they are added [50]

- Reduced permeability
- Reduction of plastic shrinkage cracking
- Increased shatter resistance
- Fire resistance

CHAPTER 3

EXPERIMENTAL WORK

3.1 Overview

This chapter shows the details of manufacturing slag / FA based GPC. The present study aimed to study the influence of molarity and two types of fibers, SF and PPF on workability and compressive, split tensile strength and energy absorption of GPC composite, all of them were studied. Alkaline liquid consists of NaOH and Na_2SiO_3.

3.2 Materials

3.2.1 Slag

GGBFS is a non-metallic material with a smooth and granular nature, containing silicates and alumina silicate of calcium. The chemical properties of GGBFS utilized in this study are seen in Figure 3.1 and summarized Table 3.1.

Figure 3.1 GGBFS used in GPC

3.2.2 Fly ash

Low calcium FA (class F) conforming to American Society for Testing Material C 618 was used for producing GPC obtained from thermal power plant called Ceyhan Sugozu, In Iskenderun-Turkey. Table 3.1 indicated to the physical and chemical properties of FA. As seen in Table 3.1 FA contained a very low percentage calcium oxide and loss of ignition as compared with OPC, the color of FA was dark as seen in Figure 3.2.

Table 3.1 physical and chemical properties of FA and GGBFS

Analysis Reports	FA	GGBFS
CaO	1.6	34.19
SiO_2	62.53	40.42
Al_2O_3	21.14	10.6
Fe_2O_3	7.85	1.28
MgO	2.4	7.63
SO_3	0.10	0.68
K_2O	3.37	-
Na_2O	2.45	-
Loss on ignition (%)	2.04	2.74
Specific gravity(g/cm^3)	2.2	2.88
Blaine fineness(m2/kg)	379	575

Figure 3.2 FA used in the geopolymer mixes

3.2.3 Aggregates

Local crushed limestone gravel utilized as a coarse aggregate with a nominal maximum size of 16 mm. And the crushed limestone sand was utilized as a fine

aggregate (FA), with a maximum size of 4 mm. the sieve analysis was conducted for both types of coarse and fine aggregates as indicated in Table 3.2.

Table 3.2 Coarse and fine aggregate sieve analysis

Sieve size (mm)	Fine Aggregate	Coarse Aggregate
16	100	100
8	99.6	31.5
4	93.7	0.4
2	58.2	0
1	37.2	0
0.5	25.4	0
0.25	5.76	0
Fineness modules	2.79	5.68
Specific gravity (g/cm^3)	2.66	2.72

(a) Coarse aggregate (b) Fine aggregate

Figure 3.3 Aggregates used in GPC mixes

3.2.4 Super plasticizer

A poly carboxylic-ether type super plasticizer (SP) was utilized in all GPC mixtures. The SP with a specific gravity of 1.07 and PH of 5.7. The properties of SP are presented in Table 3.3 as reported by the local supplier.

Table 3.3 The properties of SP

Properties	Super-plasticizer
Name	Glenium51
Color	Dark Brown
State	Liquid
Specific gravity (kg/m^3)	1.07
Description	Modified polycarboxylic type of polymer
Freezing Point	-4

3.2.5 Activating solutions

The most common activating solution utilized in geopolymerization is a combination of NaOH and glass water or Na_2SiO_3. It is recommended that the alkali-activated liquid prepared by mixing Na_2SiO_3 (glass water) and NaOH together at least 24 hours prior to utilize in geopolymer mixture. Alkaline activator solution plays a significant role in geopolymer synthesis for the dissolution of silica and alumina as well as for the catalysis of polymerization reaction [53].

In this experiment, a combination of glass water and NaOH as seen in Figure 3.4 were chosen as the alkaline liquid. The NaOH with 97% purity, in the form of pellets it was dissolved in distilled water to avoid the influence of unknown contaminants in the mixing water. The glass water commercially available, obtained from Gaziantep, Turkey (Grade A53) were utilized in the producing of GPC, a composition of 55.52% water, 29.75% SiO_2, and 14.73% Na_2O as presented in Table 3.4. The solution of NaOH was formed by dissolving it in deionized water for the molarity of 8M, 10M, and 12M. The NaOH solution was prepared 24 hours before casting of specimens.

(a) (b)

Figure 3.4 The description of activating solution, (a) NaOH, and (b)glass water

Table 3.4 The properties of Na_2SiO_3 (glass water)

Grade	A53
% NaOH (w/w)	14.7
% Na_2O (w/w)	14.73
% Si_2O (w/w)	29.75
Wt. ratio SiO_2/Na_2O	2..02
Specific gravity (gm./ml @ 20^oC)	1.46
Appearance	Viscous clear to light yellow liquid
PH	12.8
Solubility (water)	Soluble
% volatiles	> 60% (water)

3.3 Fibers

3.3.1 Steel fiber

Crimped type SF having diameter 55 µmm & length 30 mm was utilized as seen in Figure 3.5a. Aspect ratio is defined as the ratio of length to diameter.0.55 Aspect ratio was utilized in this study. The tensile strength of SF utilized is 1500 MPa & Gravity is 7850 kg /m^3.

3.3.2 Polypropylene fiber

In this investigation, PPF of 12mm in length is used (Figure 3.5b). PPF having diameter 0.03mm and were utilized in this study. The density of PPF is 910 kg/m^3.

(a) (b)

Figure 3.5 Fibers types (a) SF and (b) PPF

3.4 Mix Proportion

In the current experimental work the numbers of parameters taken into account the molarity of NaOH, Na_2SiO_3 to NaOH ratio, alkaline activator to binder ratio, types of fibers, aggregate content and curing methods. The parameters were selected according to the previous research. An alkali activator to FA ratio was 0.45 this ratio is chosen to give good strength and microstructure of the GPC [54], [55] and Na_2SiO_3 to NaOH ratio was 2.5 in additional that there was no extra water added to GPC mixture as seen in Figure 3.6. The proportions of GPC were per m^3 are presented in Table 3.5

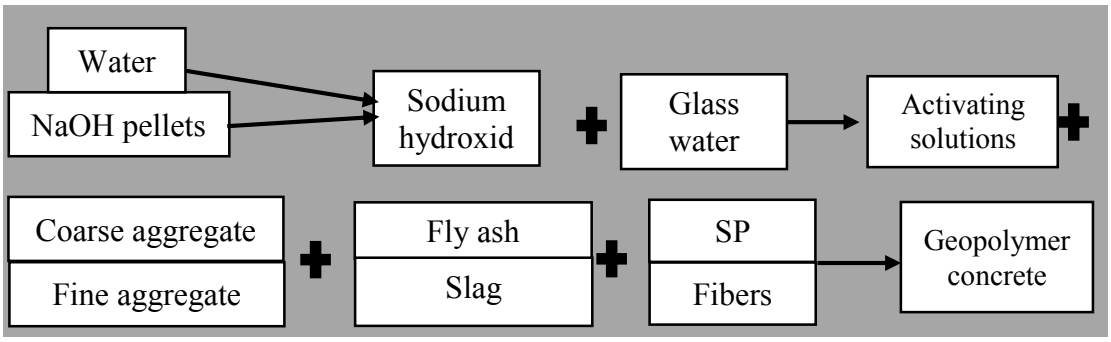


Figure 3.6 Process of manufacturing GPC

Samples code	Molarity	FA	Slag	Na_2SiO_3	NaOH		Fibers		Aggregates	
					Flakes	Water	SF	PPF	C.A	F.A
M8-SF0-P.P0	8	225	225	144.64	15.16	42.68	0	0	826.2	793.8
M10-SF0-P.P0	10	225	225	144.64	18.16	39.68	0	0	826.2	793.8
M12-SF0-P.P0	12	225	225	144.64	20.88	36.96	0	0	826.2	793.8
M8-SF1%-P.P0	8	225	225	144.64	15.16	42.68	78.2	0	826.2	793.8
M10-SF1%-P.P0	10	225	225	144.64	18.16	39.68	78.2	0	826.2	793.8
M12-SF1%-P.P0	12	225	225	144.64	20.88	36.96	78.2	0	826.2	793.8
M8-SF0-P.P0.1%	8	225	225	144.64	15.16	42.68	0	0.91	826.2	793.8
M10-SF0-P.P0.1%	10	225	225	144.64	18.16	39.68	0	0.91	826.2	793.8
M12-SF0-P.P0.1%	12	225	225	144.64	20.88	36.96	0	0.91	826.2	793.8

3.5 Manufacture of Geopolymer Concrete

3.5.1 Preparation of activating solutions

The NaOH pellets solid was dissolved in water to generate the solution as seen in Figure 3.7. The mass of NaOH solids in a solution varied according to the molarity of the NaOH. In the current study, the NaOH with 8, 10 and 12 molarity was utilized. The NaOH solution with a molar concentration of 8M consisted 8x40 = 320 grams of NaOH solids (in pellet form or flakes) per liter of the liquid, where 40 is the molecular weight of NaOH. The weight of NaOH solids was measured at 262 grams per kg of NaOH liquid of 8 molarity. Likewise, the mass of NaOH solids per kg of the liquid for other molar concentrations was measured as 10M: 314 grams, 12M: 361 grams. The NaOH and Na_2SiO_3 solution were mixed together at least 24 h. prior to preparing the alkali-activated solution. The NaOH solution was prepared by dissolving either the flakes or the pellets in water.

Figure 3.7 Preparing NaOH solution

3.5.2 Mixing and casting process

The basic process for manufacture the GPC mixtures is adopted on Standard mixing method. Aggregates are utilized as a saturated surface dry Saturated surface dry condition. Firstly, dry materials were mixed with GGBFS and FA for about 2.5 minutes. Second, the alkaline activation liquid including glass water and NaOH with super plasticizer and both steel and PPF was added to the dry materials and the

mixing continued for 3.5 minutes. After that prismatic specimen was cast and compacted in two layers, whereas cylinder specimens in three layers. Subsequently, compacted in three layers, then vibrated on a vibration table for 10s to eliminate the air voids. After casting, the molds were covered using plastic bags to avoid the vaporization of alkali solution for 24hr as a rest period. All details of mixing and casting are shown in Figure 3.8.

Figure 3.8 The details of mixing and casting of GPC

3.5.3 Capping and curing

After casting, the GPC samples were covered by the plastic bag for twenty-four hours as rest period at ambient room temperature (23°C), to prevent the evaporation of alkali-activated liquid. The GPC samples were oven cured at 80 °C temperature for 48hr nevertheless in the first 24 hr. molds opened and samples covered in plastic bags after then returned to the oven as seen in Figure 3.9. After heat cured samples stored 28 days at ambient room temperature 23°C until the time test.

Figure 3.9 Stored and curing GPC samples

3.6 Test Procedure

3.6.1 Slump test

The Slump test is an experimental method that measures the viability of fresh concrete. More precisely, it measures the consistency and variations in uniformity of the concrete in a specific batch. The apparatus used for this test is a hollow frustum of a cone with specifications seen in Figure 3.10.

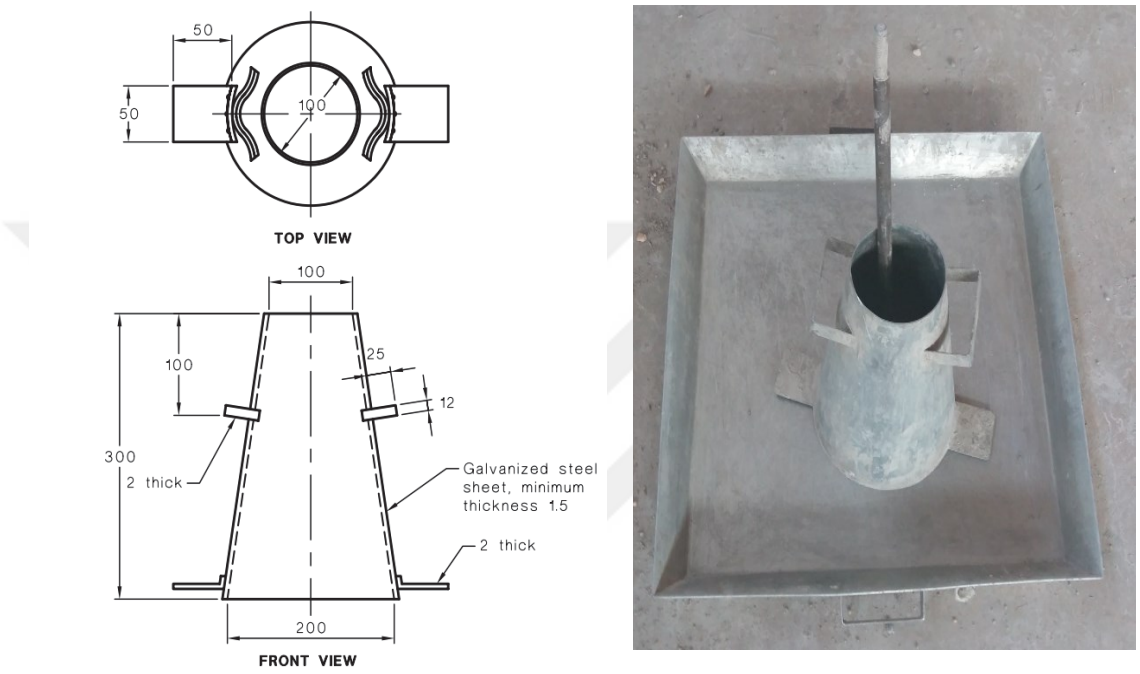


Figure 3.10 Type mold for slump test

The slumped concrete may take one of the three forms; shear, true and collapse slump as seen in Figure 3.11 if concrete is slumping equally all rounds, called a real slump, which is of utility in the tests. If instead of a true slump, half of the cone slides down a jet inclined, and it is said that the shear slump has occurred. In this case, the test should be repeated and if the shear slump continues, this indicates a lack of cohesion in the mix. It may subject bleeding and segregation thus is not desirable. A collapse slump generally means that the mix is too wet or there is a high workability level, for which the slump test is not appropriate. The concrete slump values may vary in the range between zero (no slump-very low workability) to collapse.

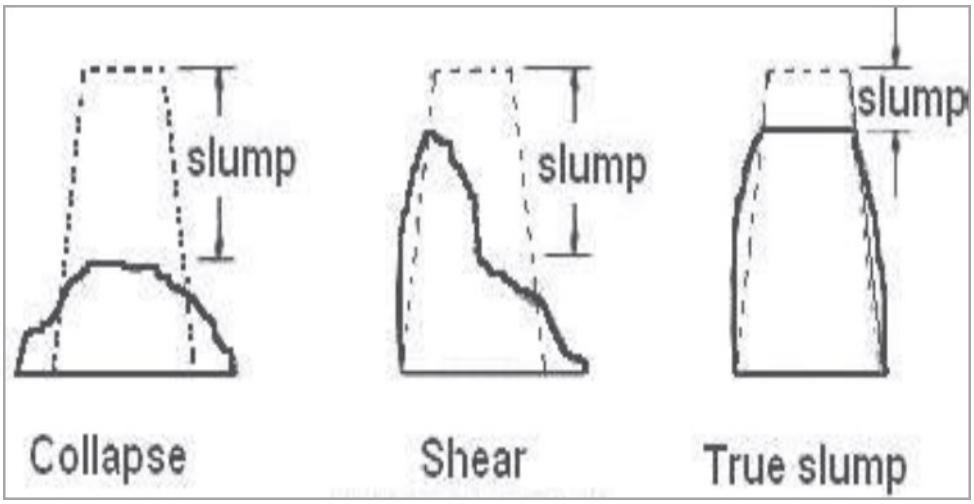


Figure 3.11 Different profiles of concrete slump

3.6.2 Compressive strength

The compressive strength test is the most common of all tests on concrete hardness. This is partly because it is an easy test to achieve. Moreover, many of desired properties of concrete are qualitatively related to its compressive strength. However, the chief reason for compressive test popularity is the inherent significance of the compressive strength in concrete structural design [56]. In Standard, a method of testing concrete, only cylindrical specimens which are prepared in accordance with (ASTM C39, 1997) [56] are accepted to be tested to determine the concrete compressive strength. Therefore, all compressive tests are performed on cylindrical specimens of 100 mm diameter with 200 mm length following (ASTM C39, 1997) [56] procedural requirements. Prior to the test, concrete samples were properly capped complying with the latterly mentioned standard. For each concrete type, compressive strength test is performed at 28 days of age and for each age, 3 cylindrical samples were tested. The compressive strength of the samples is estimated by dividing the maximum force applied to the specimen by the cross-sectional area. This area is calculated from the average of the two measured diameters. As seen in Figure 3.12.

Figure 3.12 The compression strength machine

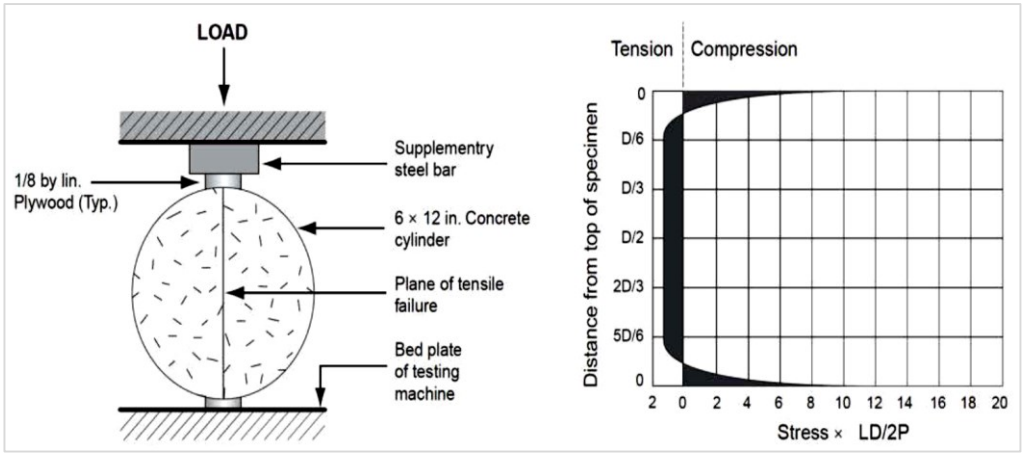
3.6.3 Split tensile strength

The split tensile test ('Brazil' or splitting test) is a simple and indirect way of determining the tensile strength of concrete, which gives more consistent results than other tension tests. The measured strength of the split test is believed to be close to the direct tensile strength of the concrete and approximately 5 to 12 percent higher [57].

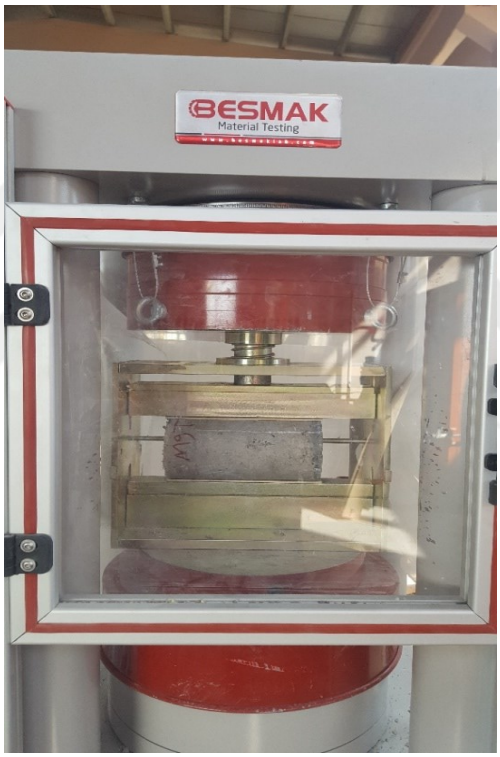
In this study, the split tensile test is conducted in accordance with (ASTM C496, 2004) [58] on cylindrical specimens of 100 mm diameter by 200 mm length. The concrete cylinder is placed, with its axis horizontal, between the plates of the testing machine as seen in Figure 3.13 is loaded until the failure takes place by indirect tension in the form of splitting along the vertical diameter. For each concrete kind, the split tensile test is performed at 28 days of age and for each age, 3 cylindrical samples are tested. The split tensile strength of the specimen can be estimated using equation;

$$f_{ct}, S_p = \frac{2P}{\pi LD} \tag{3.1}$$

Where f_{ct}, S_p is the splitting tensile strength in MPa, P is the peak-applied load in kN, L is the sample length in mm, and D is the diameter in mm.



(a)



(b)

Figure 3.13 Splitting tensile tests (a) left side is typical arrangement of the test and right is stress distribution across the loaded diameter of a cylinder compressed between two plates and (b) machine test

3.6.3 Fracture parameters

A closed-loop testing machine with a capacity of 250 KN was utilized to measure the fracture energy (G_F) of prismatic samples based on the recommendation of RILEM 50-FMC/198 Committee [59]. To estimate the displacement at mid-span of prismatic samples, a linear variable displacement transducer (LVDT) was utilized. The ratio of

the notch to depth (a/w) for prismatic specimens was 0.4 and the notch opened for prismatic test specimens by cutting in order to minimize the effective cross-section to 60 ×100 mm^2 and the distance between supports was 400 mm as shown in Figure 3.14. Fracture energy of prismatic beam specimens was obtained under three-point loading to according RILEM [59] as follow:

$$G_f = \frac{\left(w_o + mg\delta_s\right)}{A_{lig}} \quad (3.2)$$

Where W_o, m, g, δs, and A_{lig} are the area under the load-displacement curve (N-m), the mass of the beam (Kg), the acceleration due to gravity (9.81m/s^2), specific displacement (m) and A_{lig} are the area of the ligament (m^2) respectively.

The flexural peak strength (f_p) calculated according to ASTM C1609 [60].

$$f_p = \frac{P_p L}{bd^2} \quad (3.3)$$

Where P_p, L, b and d are peak load (N), length of span (mm), beam width and depth of the beam.

The net flexural strength, (f_{flex}), was obtained based on the following equation[61]:

$$f_{flex} = \frac{3P_{max} S}{2B(W-a)^2} \quad (3.4)$$

where $3P_{max}$, S, B, W and a are the peak load (N), span length (mm), the width of the beam (mm), depth of beam (mm) and depth of the notch (mm) respectively.

The critical stress intensity factor (K_{IC}) was utilized to identify the magnitude of stress concentration in cracks. The K_{IC} values were obtained based on equation (3.5) [62].

$$K_{IC} = \frac{3P_{max} l}{2bd^2}\sqrt{a_0}\left(1.93 - 3.07A + 14.53A^2 - 25.11A^3 + 25A^4\right) \quad (3.5)$$

Where, P_{max} , l, b, d, and a_o are the peak load, the span of the beam, the width of the beam, the depth of beam and the depth of the notch ($A = a_o/d$).

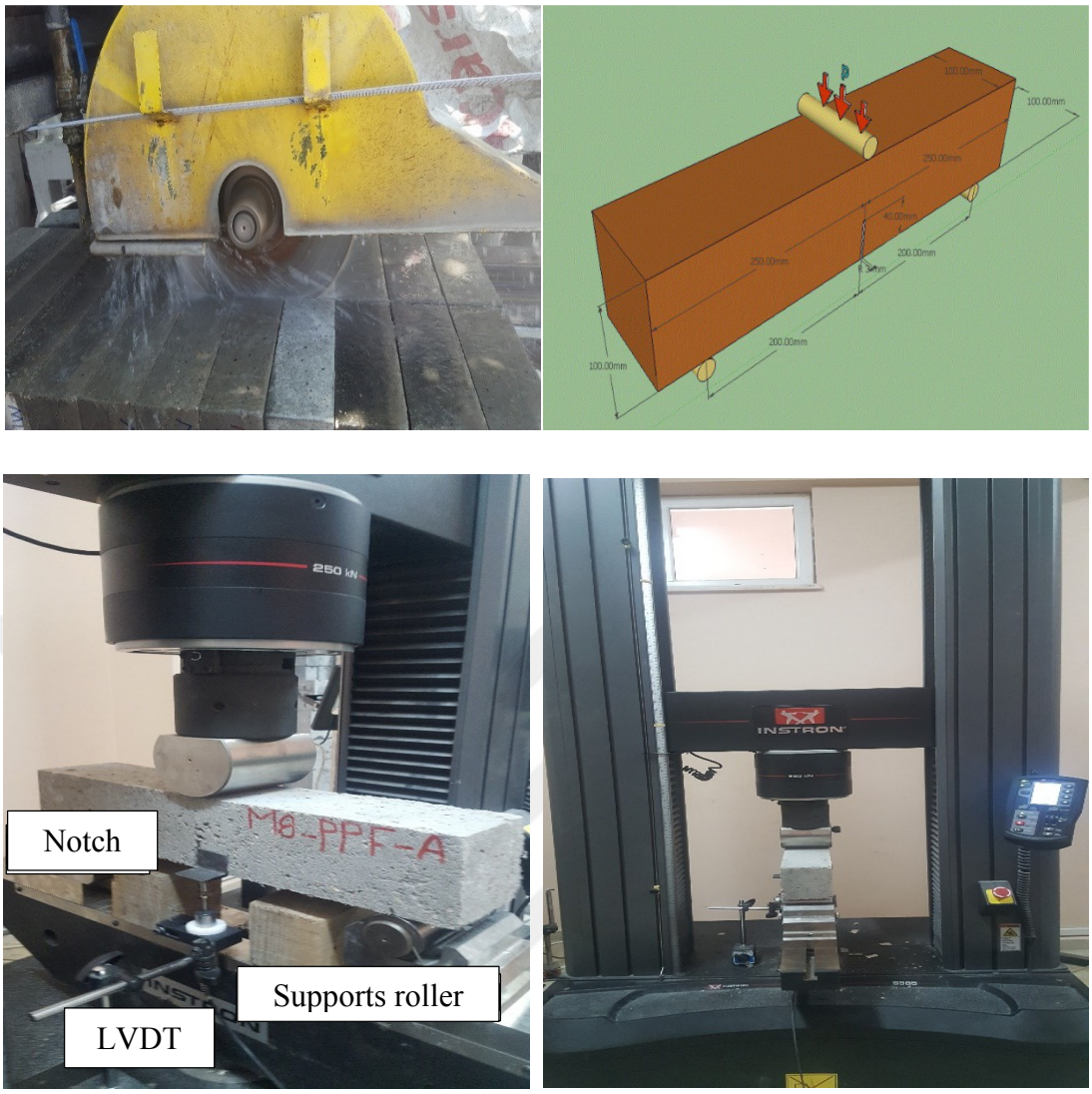


Figure 3.14 The details for fracture toughness

CHAPTER 4

RESULTS AND DISCUSSIONS

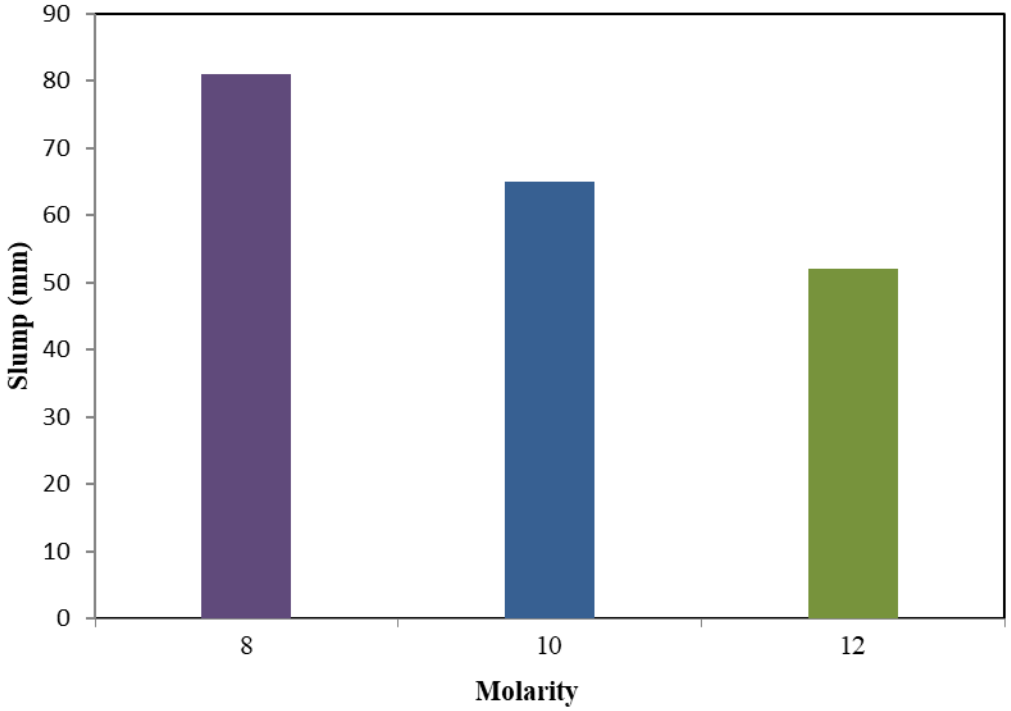
4.1 Workability of Geopolymer Concrete

The workability of the fresh FA / slag (FA/GGBFS) based GPC was tested immediately after mixing. The average workability of the GPC mixes without fibers was higher than mixes with SF and PPF. The workability of control mixes (without fibers) was ranging from 81mm to 52mm because the increase in the molarity of alkali-activated based GPC leads to diminishing the workability as seen in Figure 4.1a and indicated in Table 4.1. Moreover the quantity of slag and FA in the matrix of GPC had a great impact on the fresh properties of GPC especially on the workability because the slag and FA have a spherical shape which making matrix more transportable than the sharper particles of ordinary cement as stated in Chapter two.

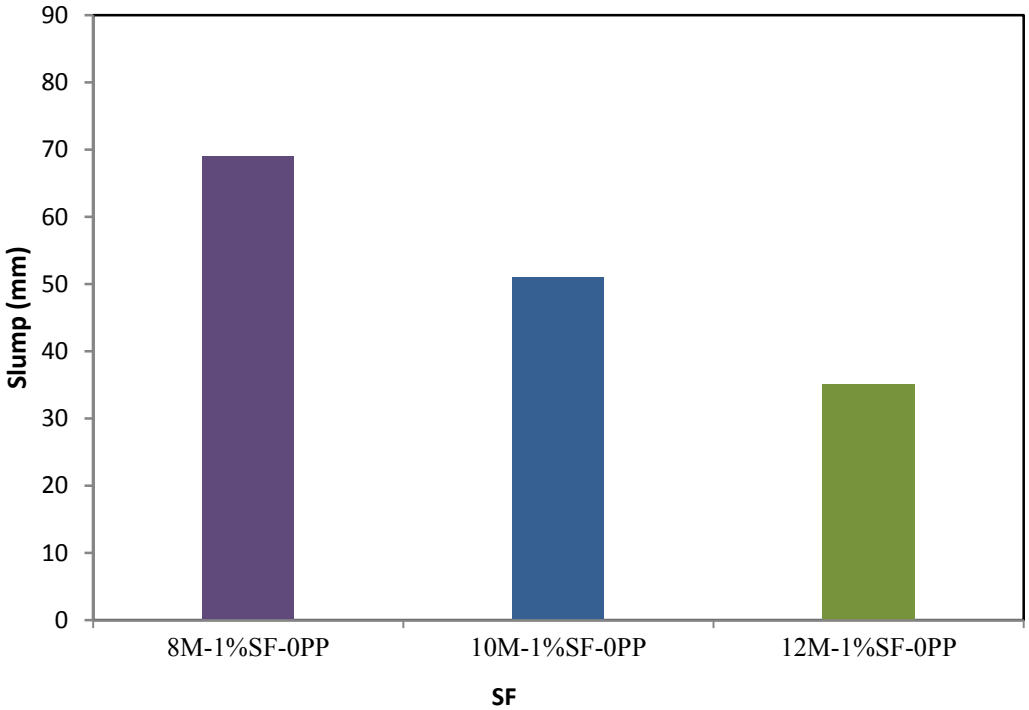
In another hand, the incorporation of fibers in GPC caused an obvious decrease in the workability of GPC as summarized in Table 4.1 Furthermore the addition of PPF in GPC causes a higher decrease in workability than SF as seen in Figure 4.1c. This reduction in workability of GPC can illustrate the large surface area of SF and PPF absorbed more alkali-activated solution and water around the fibers which reduced the workability and improved the viscosity of GPC.

Table 4.1 The slump cone of GPC

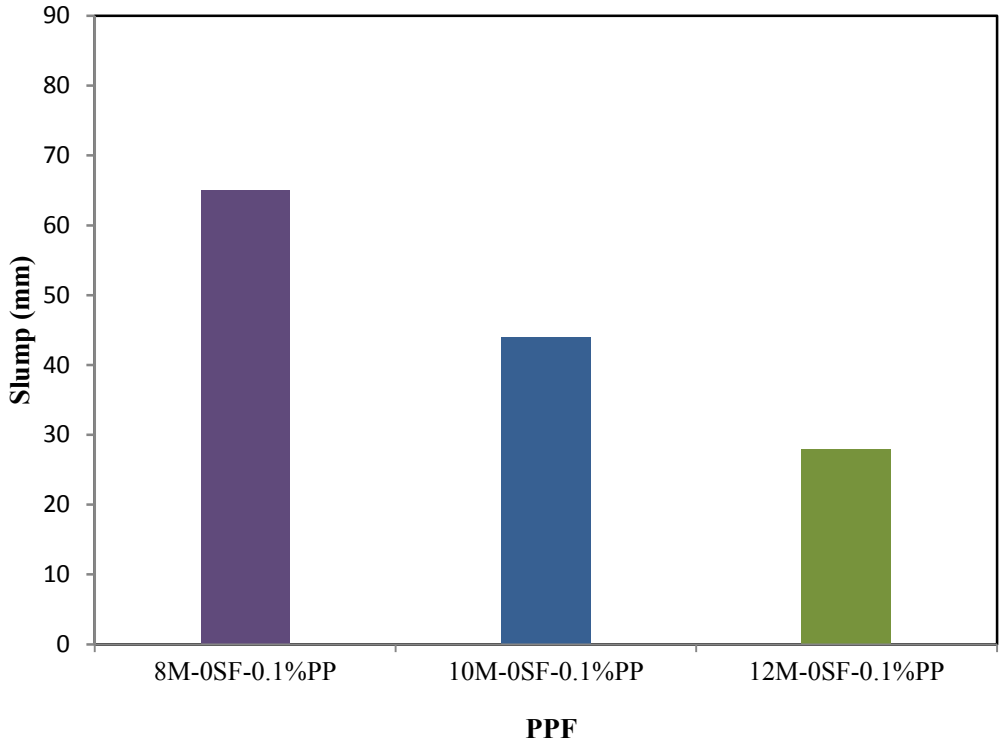
Molarity	Control	SF	PPF
8	81.0	69	65
10	65	51	44
12	52	35	28


90
80
70
60
50
40
30
20
10
0
Slump (mm)
8
10
12
Molarity

(a)


90
80
70
60
50
40
30
20
10
0
Slump (mm)
8M-1%SF-0PP
10M-1%SF-0PP
12M-1%SF-0PP
SF

(b)



(c)

Figure 4.1 the workability of fly ash/slag based GPC under the influence (a) Control Mix, (b) SF and (c) PPF

4.2 Compressive Strength

The compressive strength of FA/GGBFS based GPC with and without fibers samples at three ages 7, 28 and 56 days and cured 80 °C temperature for 48hr is listed in Table 4.2 and Figure 4.2a, b, and c. Three identical cylinder samples were used to take an average for each value of the results. The first group was plain GPC and the results revealed that the compressive strength of plain GPC samples develops with increasing time. However, this increment considered not effect as seen in Table 4.2 the compressive strength of 8M samples increased about 6% and 16% after 28 and 56 days as compared with 7 days. Tthe similar behavior for 10 and 12 molar concentrations samples which slightly improved with increasing time that's attributed to the most compressive strength of FA / slag based on GPC is achieved at a temperature of 80 °C and the heat cured is contributed by acceleration of geopolymerization reaction of GPC samples [63].

As seen in Figure 4.2a and Table 4.2 the increase in the molarity of alkali-activated solution based GPC leads to increase in compressive strength of FA/GGBFS based GPC. The maximum enhancement in compressive strength of GPC observed in

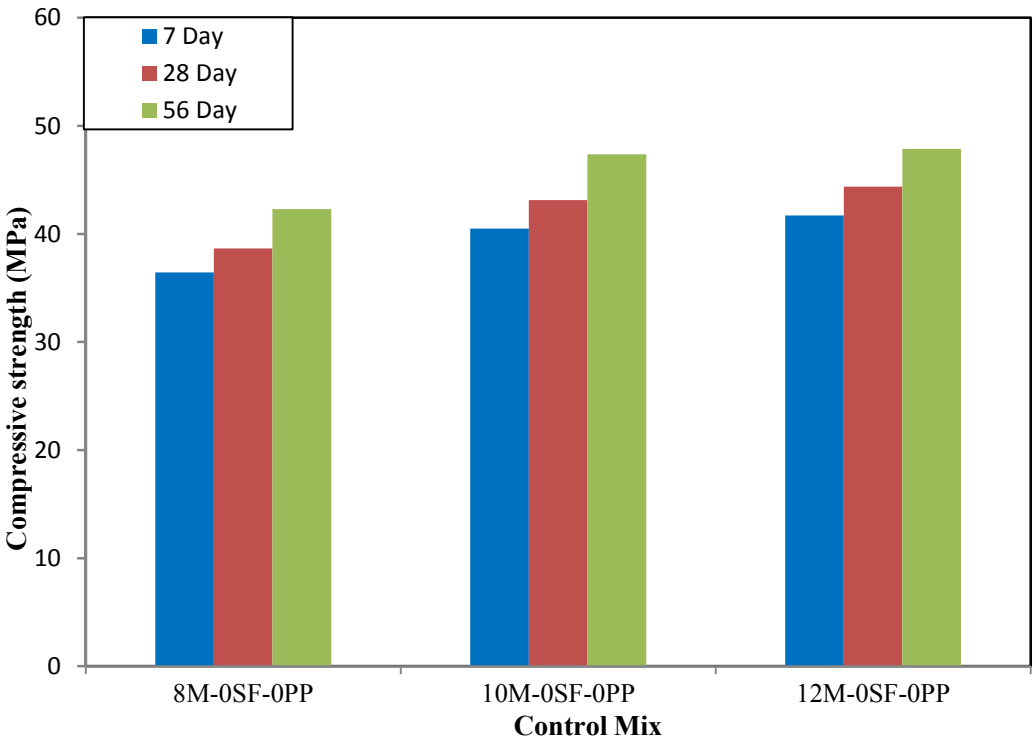
molar concentration with 12M was 47.87 MPa at 56 days while the minimum compressive strength was 42.31 MPa with 8M and at the same time. Increasing the molar concentration of Na_2SiO_3 from 8 M to 12 M resulted in a development of compressive strength of GPC samples about 14.45%, 14.76% and 13.14% for 7, 28 and 56 days respectively subjected to 80 °C heat curing in an oven.

The second group was FA / slag based GPC blended with 1% SF as seen in Figure 4.2b and listed in Table 4.2. The results showed that the addition of SF to the mixture had a clear influence on early and long-term compressive strength of plain GPC specimens. The maximum improvement was recorded at 12 molar concentration of Na_2SiO_3 and 1% SF (12M-1%SF) while the minimum improvement obtained at 8M and 1% SF (8M-1%SF). Addition 1% SF to the plain GPC with 12 molar concentration of NaOH enhanced the compressive strength by 6.1%, 8.4% and 8.2% for 7, 28 and 56 days respectively. It is as compared with plain GPC this significant improvement attributed to the high content of GGBFS 50% blended in the mixes which makes high strong bond between SF and plain GPC moreover this finding agrees with the resulted stated by Piti et al [64] and Al-Majidi et al [65].

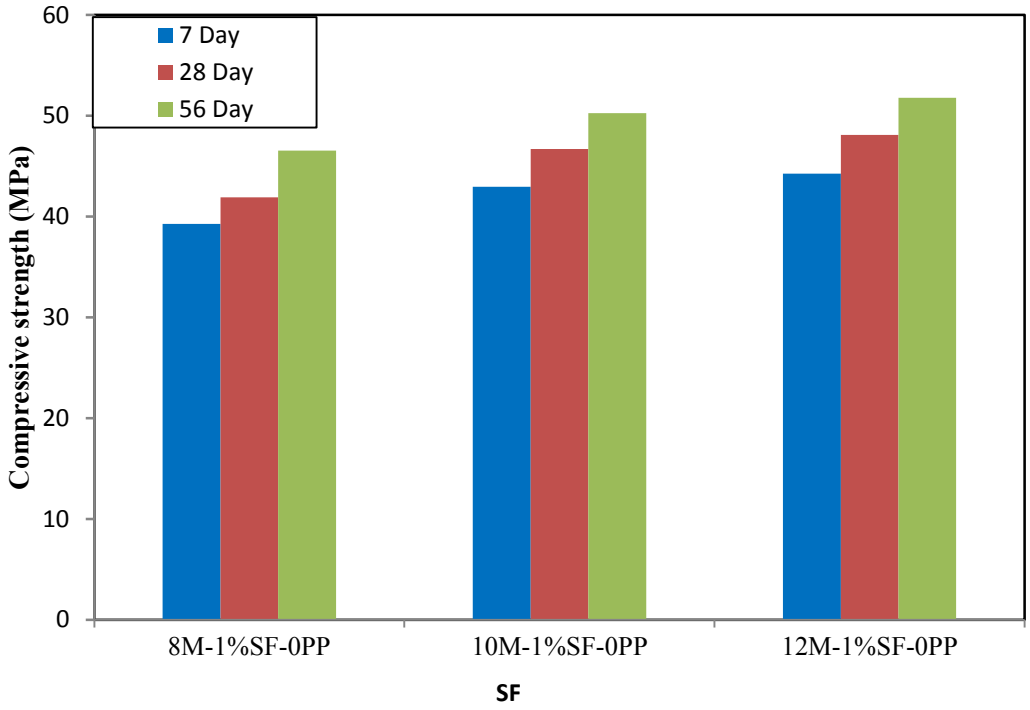
The third group was FA / slag based GPC incorporated with 0.1% of PPF as seen in Figure 4.2c. As seen in results the inclusion of PPF had clear impact on early and long-term compressive strength of the plain GPC, the compressive strength of PPF based GPC (PPFGPC) was detected to be reduced slightly from 38.67 to 37.66 MPa, 43.13 to 42.67 MPa and 44.38 to 44.24 MPa for 8M, 10M and 12M respectively at 28 days. The reduction of compressive strength attributed to the high voids inside materials, poor compaction and the sensitivity of PPF to heating furthermore PPF is a highly flexible material and the volume fraction of PPF causes the geopolymer matrix to become loose and porous [64]. The relationships between the compressive strength and workability of different molar concentration and fiber reinforced GPC are seen in Figure 4.3a, b and c, the increase in the molarity of NaOH lead to reduce the workability of GPC that means the increase in concentration resulting increasing in solid materials of NaOH. The increase in compressive strength resulting in a reduction in workability because the adding fibers increase the bond between materials particles and alkali-activated solution.

Table 4.2 The compressive strength values plain GPC and reinforced GPC by steel and PPF at different ages

Mixes code	Ages		
	7 Days	28 Days	56 Days
8M-0SF-0PP	36.45	38.67	42.31
10M-0SF-0PP	40.49	43.13	47.36
12M-0SF-0PP	41.72	44.38	47.87
8M-1%SF-0PP	39.27	41.91	46.53
10M-1%SF-0PP	42.97	46.71	50.27
12M-1%SF-0PP	44.27	48.1	51.79
8M-0SF-0.1%PP	36.34	37.66	39.98
10M-0SF-0.1%PP	40.41	42.76	46.91
12M-0SF-0.1%PP	41.61	44.24	48.27



(a)



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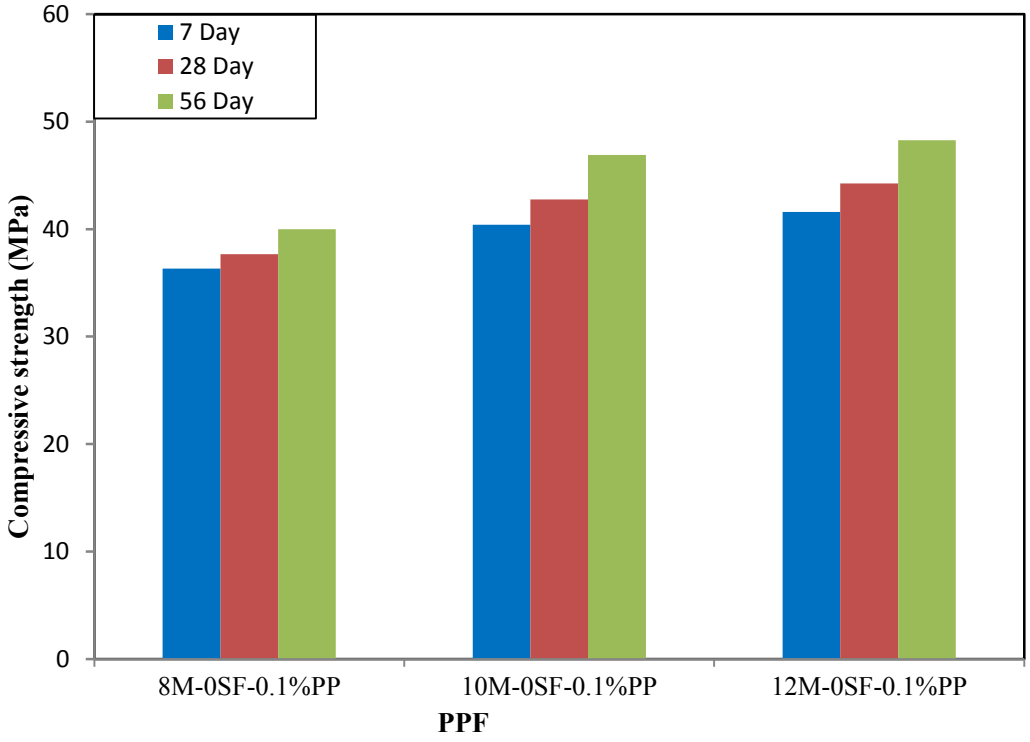
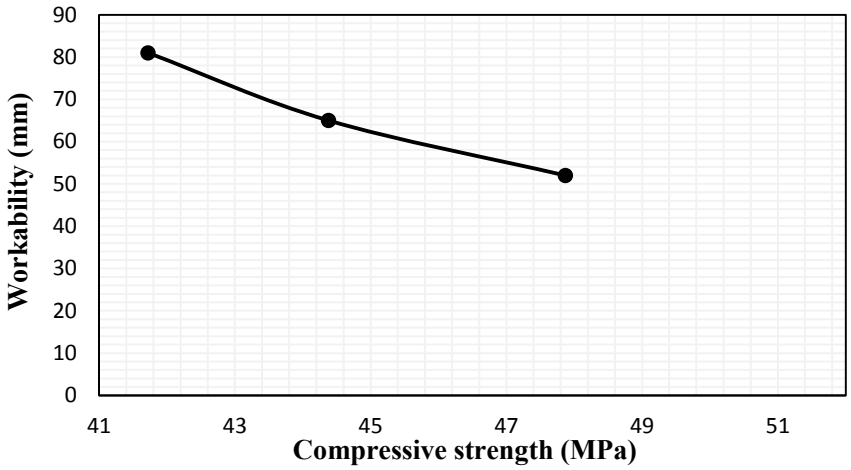
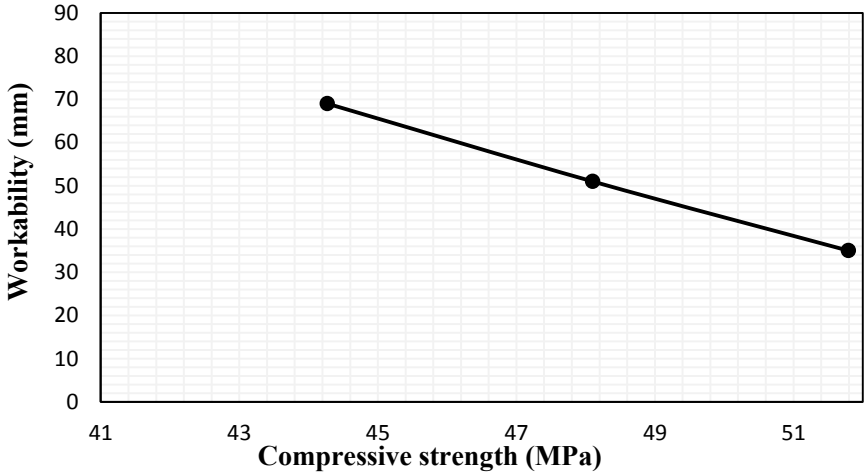


(c)

Figure 4.2 The compressive strength of fly ash/slag based GPC with fibers



(a)



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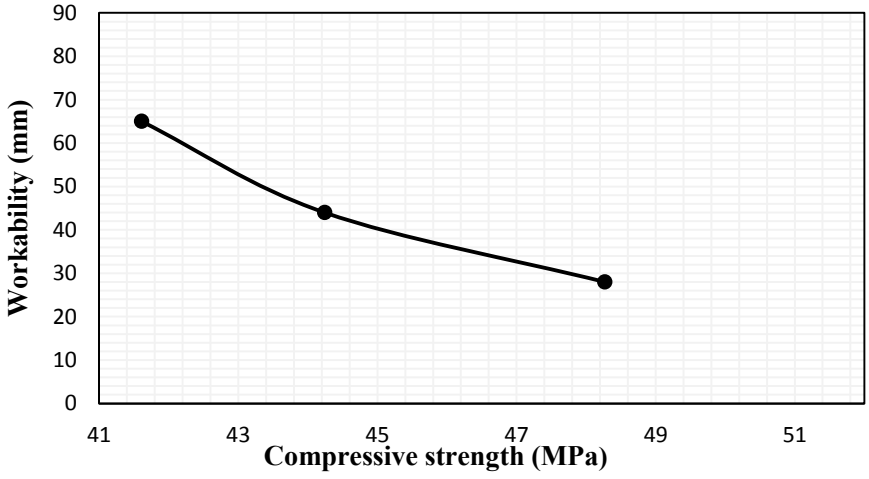


(c)

Figure 4.3 The relationship between compressive strength and workability (a) Control mix, (b) with SF and (c) with PPF

4.3 Splitting Tensile Strength

The splitting tensile strength of FA / slag based GPC with and without fibers specimens at three ages 7, 28 and 56 days and cured 80 °C temperature for 48hr was determined and calculated according to Eq. (3.1). The results are summarized in Table 4.3 and Figure 4.4a, b and c, showing a slightly improving in splitting tensile strength of plain GPC when the molarity of NaOH increased because the dissolution process is more sufficient with an increasing NaOH concentration, yielding higher splitting tensile strengths furthermore the short and long term resulting in improved splitting tensile strength increased.

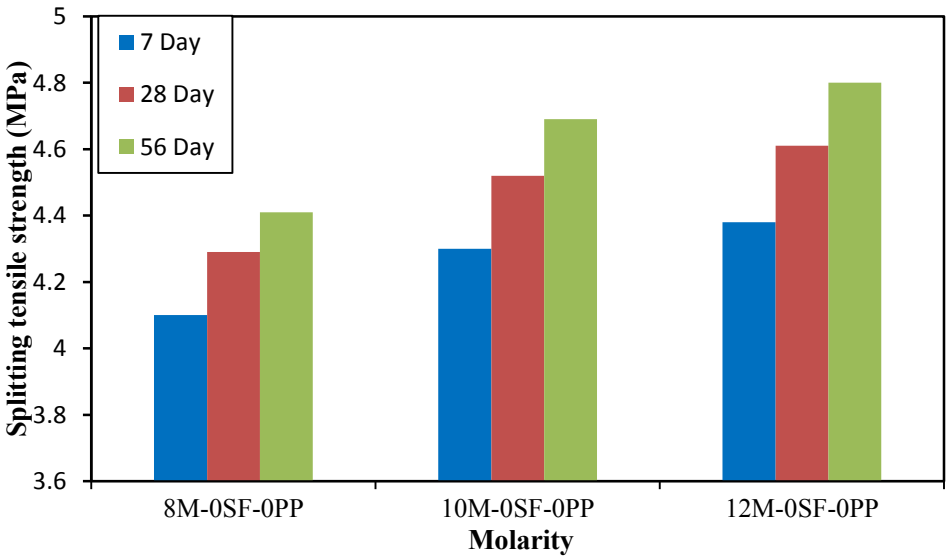
The incorporation 1% of SF in FA/GGBFS based GPC showed superior splitting tensile strength as shown in Figure 4.4b. the addition of SF to the GPC considerably enhances the post-crack load carrying capacity because of the reinforcing influence of the SF in all tested mixtures which resulting in to change in the failure mode from brittle (sudden failure) to the ductile because of the SF makes a bridges between GPC particles and minimized crack coalescence [65]. The results showed that the adding of SF enhanced the splitting tensile strength by 44.9%, 44.2% and 44% for 8M, 10M, and 12M respectively. Also, if it is compared with plain GPC at 56 days this is due to replacement of FA which considered low reactively material by highly pozzolanic material (GGBFS) in the binder which accelerates the geopolymerization process. That lead to improve the bond between the matrix and SF Subsequently increasing the energy requirements for the fracture process also the results exhibited that the curing period plays a major role in the tensile strength improvement of SF reinforced GPC.

The addition of 0.1% of PPF to plain GPC had an important development in splitting tensile strength in contract to the compressive strength that reduced when PPF added as seen in Figure 4.4c. The splitting strength of the GPC reinforced by PPF showed higher values than that detected for plain GPC (Table 4.3). This behavior can be attriuted to the ability of PPF to reduce the fine cracks in the GPC matrix. The maximum splitting strength were recorded at 12M of NaOH concentration at 56 days the addition of PPF contributed to building bridges across the split portions of the GPC matrix performed through the stress transfer from the matrix to the fibers and thus, slowly reinforced the entire load. The stress transmission developed the tensile strain capacity of the fiber reinforced GPC and therefore, enhanced the splitting

tensile strength of the PPF reinforced GPC over the plain GPC [66]. The relationships between the splitting tensile strength and workability of different molar concentration and fiber reinforced GPC are seen in Figure 4.5a, b and c, the increase in the molar concentration of NaOH resulting in a reduction the workability of GPC. The increase in splitting tensile strength of fiber reinforced GPC leads to diminishing in workability because the addition fibers increase the bond between materials particles and alkali-activated solution as shown in Figure 4.5b and c. Figure 4.6 indicates the relationship between the compressive and splitting tensile strength in existence of different molarity and fibers.

Table 4.3 The splitting tensile strength values plain GPC and reinforced GPC by steel and PPF at different ages

Mixes code	Ages		
	7 Days	28 Days	56 Days
8M-0SF-0PP	4.1	4.29	4.41
10M-0SF-0PP	4.3	4.52	4.69
12M-0SF-0PP	4.38	4.61	4.8
8M-1%SF-0PP	5.74	6.17	6.39
10M-1%SF-0PP	6.02	6.49	6.76
12M-1%SF-0PP	6.14	6.62	6.91
8M-0SF-0.1%PP	4.79	5.12	5.36
10M-0SF-0.1%PP	5.03	5.39	5.68
12M-0SF-0.1%PP	5.13	5.5	5.73



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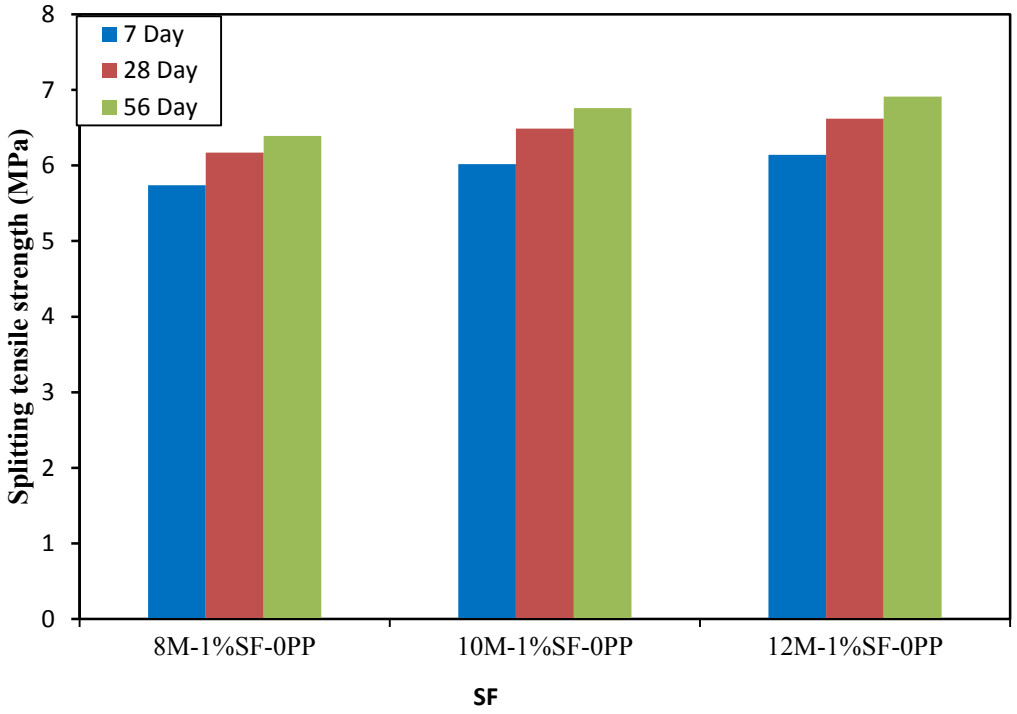

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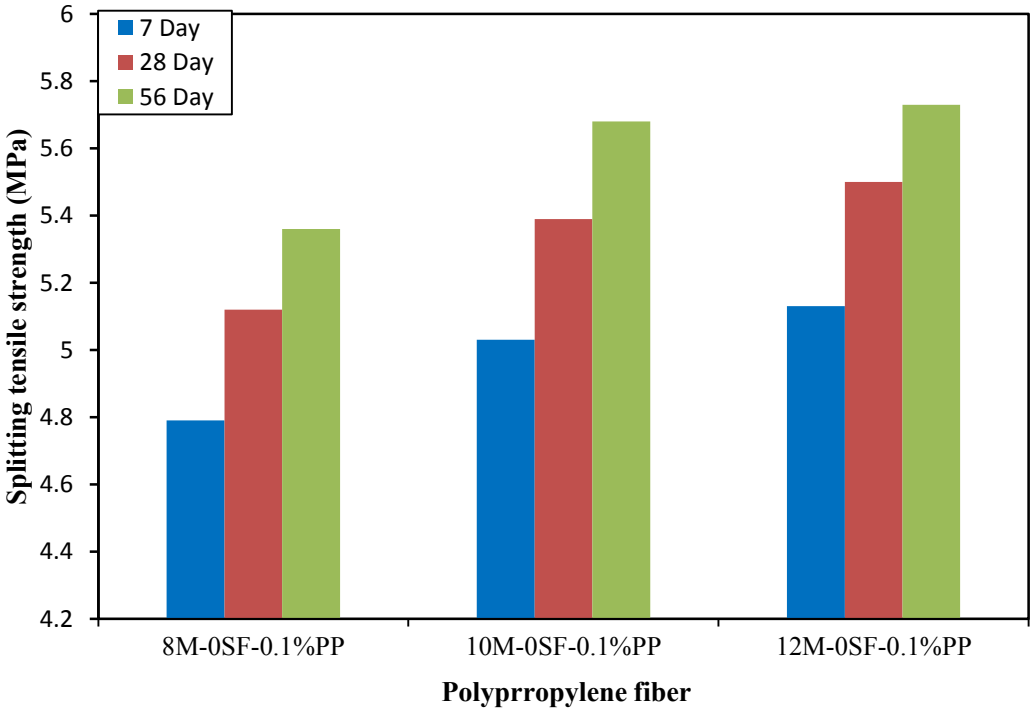
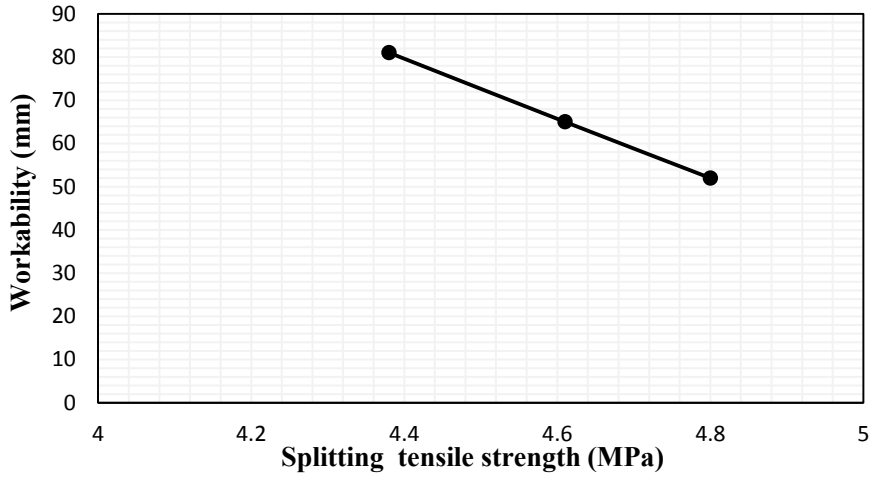
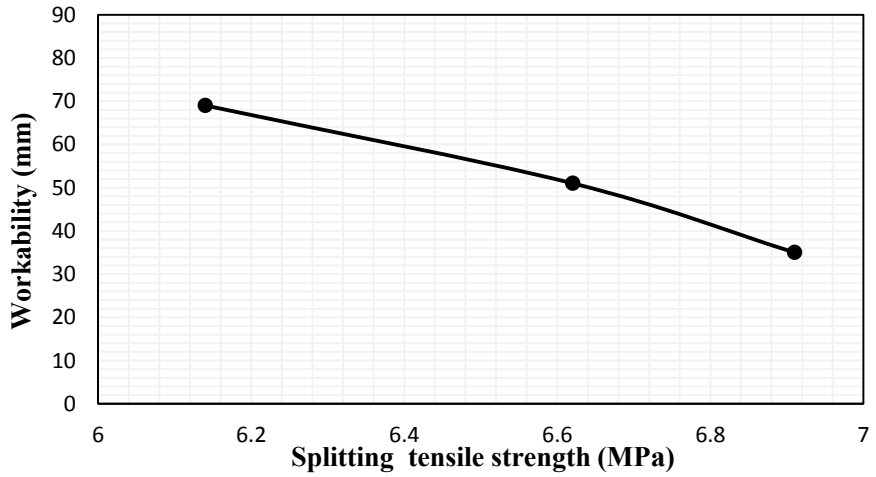


(c)

Figure 4.4 The splitting tensile strength of FA/GGBFS based GPC with fibers



(a)



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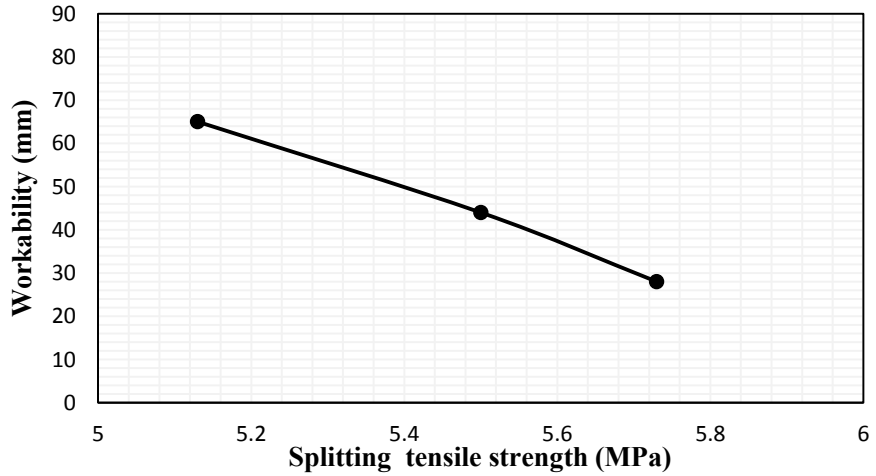
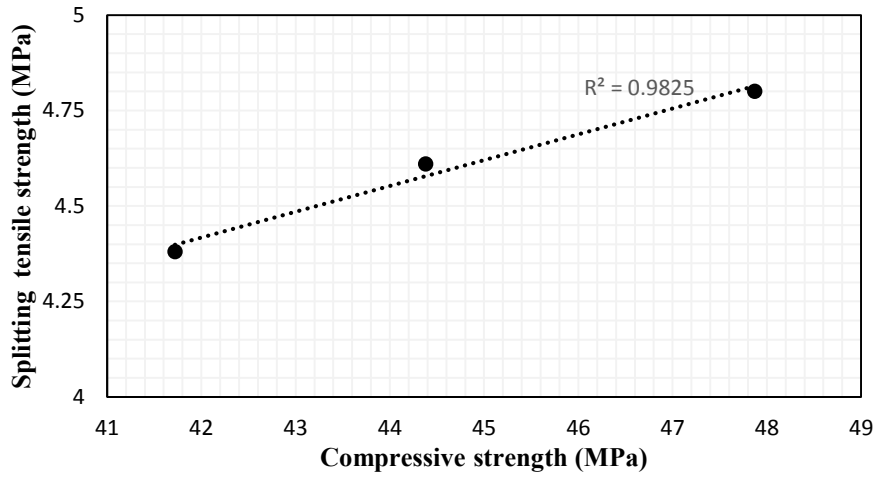
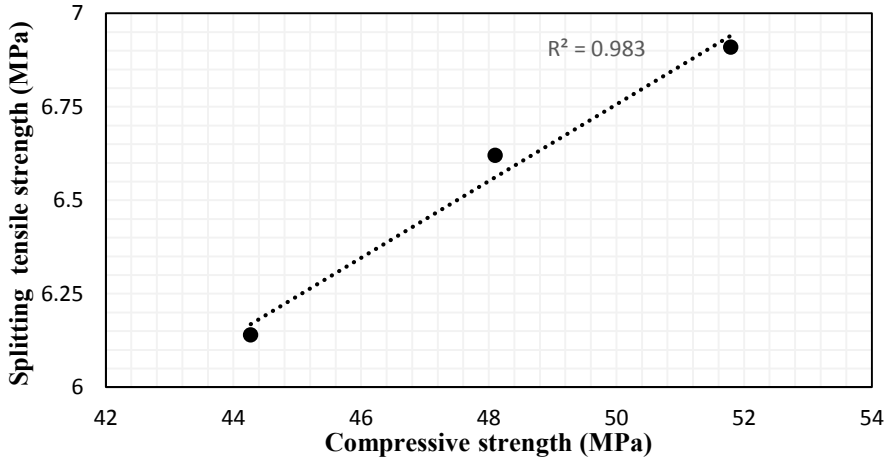


(c)

Figure 4.5 The relationship between compressive strength and workability (a) Control mix, (b) with SF and (c) with PPF



(a)



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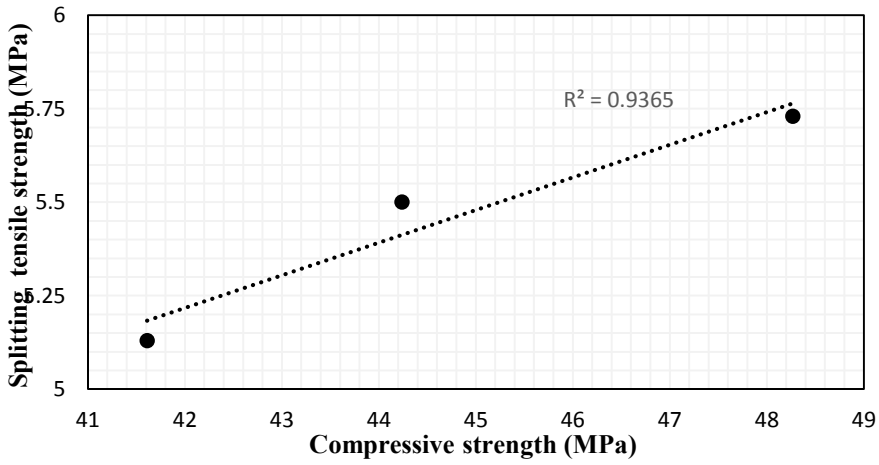


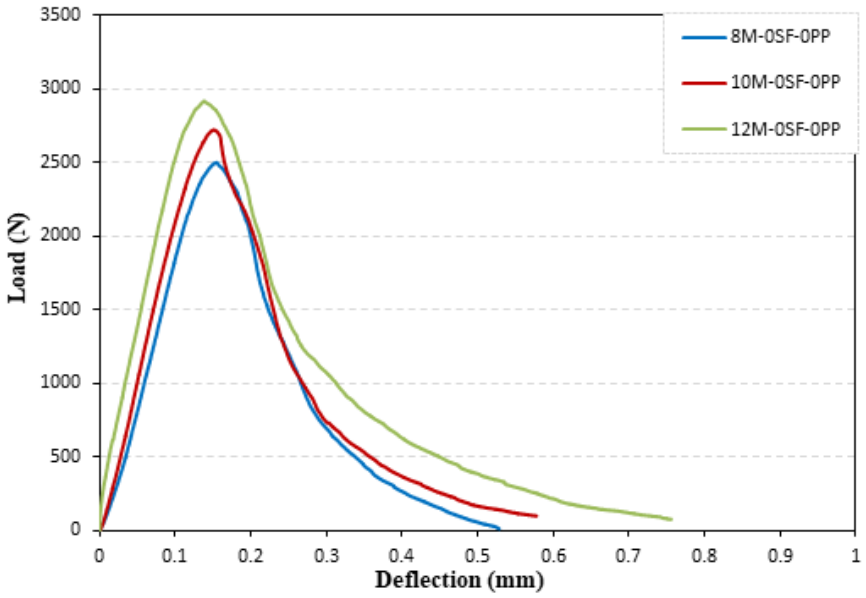
(c)

Figure 4.6 The relationship between splitting tensile and compressive strength (a) Control mix, (b) with SF and (c) with PPF

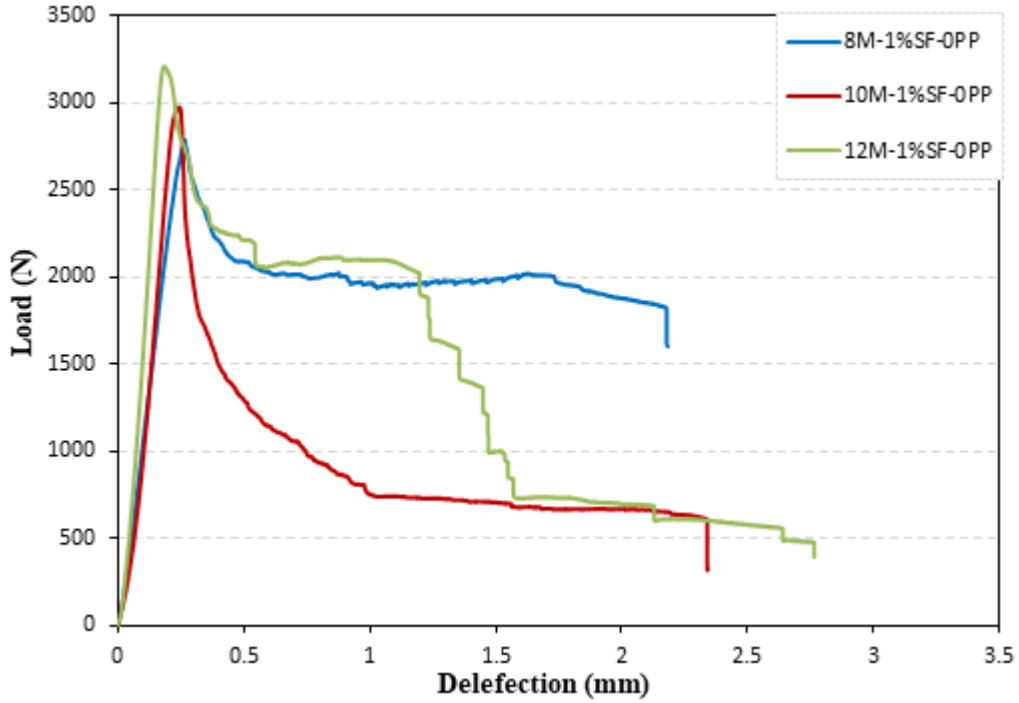
4.4 Load Deflection Behavior

The load-deflection patterns of plain geopolymer and fibers reinforced GPC cured at 80 °C temperature up to 48 hr. and tested at 56 days presented in Figure 4.7a,b and c and the results were summarized in Table 4.4, eighteen beams were tested at three-point load. As usual, all plain GPC and fiber reinforced GPC curves exhibited a linear upward slope till load at first cracking of specimens. After the load during the test reach the peak load, the cracks appeared which resulted in a descending curve after peak load. However, the slope of descending part of the curve after peak represented the property of the crack propagation inside the specimen until failure.

It is detected from Figure 4.7a, b and c that the load-deflection of fiber reinforced GPC specimens shows remarkably increase than plain GPC specimens because of the addition of SF to plain GPC. considerably enhances the post-crack load carrying capacity resulting in the effect of reinforcing of SF in all tested mixtures. it is which leads to change the property of GPC from sudden failure (brittle) to ductile failure moreover the addition of fibers makes bridging between the matrix of GPC and SF which helps to decrease crack coalescence [67]. The specimens of PPF-GPC showed more deflection than SF reinforced GPC specimens that are attributed to the PPF increased strain to failure: a fine cracked free finish also the PPF considered high impact resistance.



(a)



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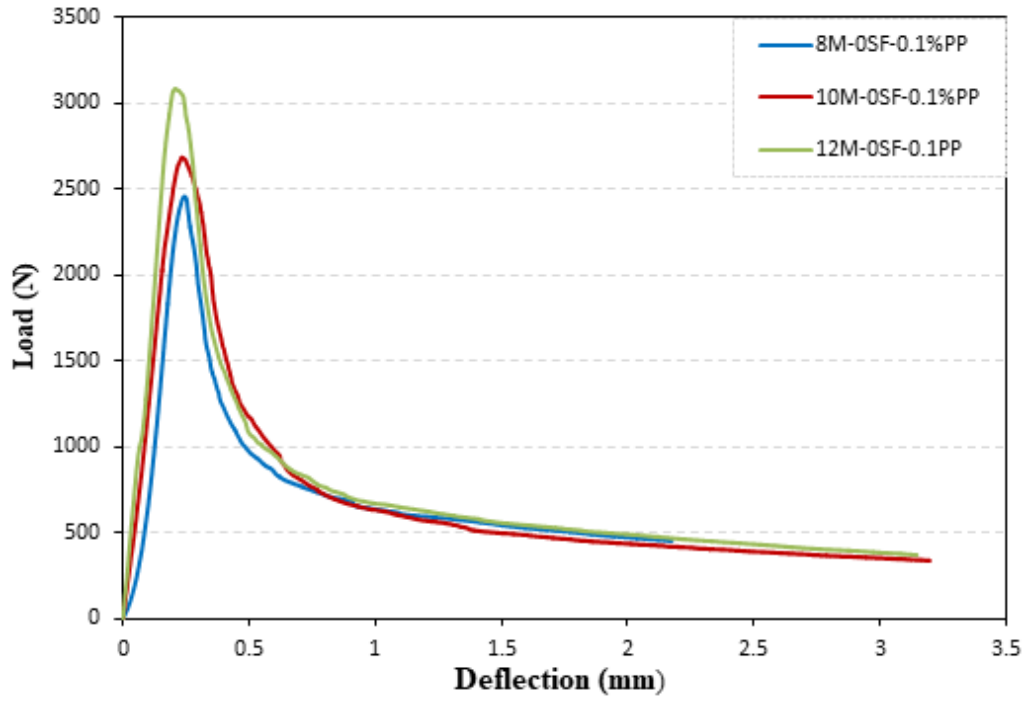


(c)

Figure 4.7 Typical load vs deflection curves of plain GPC and fiber reinforce GPC specimens (a) Control mix, (b) with SF and (c) with PPF

Table 4.4 Flexural strength and fracture properties of plain and fibers reinforced GPC

Mixes code	Peak Load (N)	Flexural strength (MPa)	Net flexural (MPa)	Deflection (mm)	Area under curve (N-mm)	Fracture energy (N/m)	K_{IC} (MPa-$mm^{0.5}$)
8M-0SF-0PP	2502	1.25	4.17	0.53	495.17	92.28	19.75
10M-0SF-0PP	2725	1.36	4.54	0.58	561.85	104.27	21.51
12M-0SF-0PP	2921	1.46	4.87	0.76	741.17	137.57	23.06
8M-1%SF-0PP	2790	1.40	4.65	2.18	2190.55	406.59	22.02
10M-1%SF-0PP	2978	1.49	4.96	2.34	2560.50	471.58	23.51
12M-1%SF-0PP	3212	1.61	5.35	2.76	3810.37	687.24	25.36
8M-0SF-0.1%PP	2560	1.28	4.27	2.18	1727.88	328.77	20.21
10M-0SF-0.1%PP	2788	1.39	4.65	3.20	2298.60	444.52	22.01
12M-0SF-0.1%PP	3089	1.54	5.15	3.15	2364.87	456.71	24.38

4.5 Fracture Energy

The area under the load-deflection curve for each prismatic sample was estimated and utilized in Eq. (3.2) at section 3.6.3 to calculate the fracture energy (G_F) of each beam and Table 4.4 indicates the results of fracture energy of FA/GGBFS based GPC with different fibers. The fracture energy (G_F) for all mixes are represented in Figure 4.8. The results showed that the increase in the molar concentration of NaOH for plain GPC matrix generally improved the fracture energy absorption because the increase of concentration helps to improve the geopolymerization of GPC. The area under the load-deflection curve and fracture energy of fiber reinforced GPC is listed in Table 4.4. it can be detected that the employment of fibers in GPC considerably

increased the area under the load-deflection curve and fracture energy due to the existence of FA and slag in geopolymer matrix which improves the energy absorption in adding that the impact of fine-grained GGBFS and FA on the pozzolanic activity helps to develop the bond between matrix and SF. The fracture energy of SF reinforced GPC observed more than the fracture energy of PPF reinforced GPC. A similar finding was also stated by Piti Sukontasukkul et al. and Deepa Raj et al. [64], [68], they reported that the fracture energy and fracture toughness of SF reinforced GPC were observed to increase with increase of fiber content also they found that the SF reinforced GPC provide a higher area under load-deflection curve and fracture energy than PPF reinforced GPC.

Mechanical strength relationships of the samples under different parameters were given in (Figure 4.9 and 4.10). Generally, the G_F of plain GPC and fiber reinforced GPC inclined to increase with an increase in compressive strength as seen in Figure 4.9. Sarker et al. [69] investigated that the fracture energy improved with the increase of compressive strength for heat cured FAGPC. The value of G_f is also increased with an increase in split tensile strength of concrete as seen in Figure 4.10. A good relationship between compressive strength and fracture energy was observed (R^2: 0.96, 0.906 and 0.72) for plain GPC, SF reinforced GPC and PPF reinforced GPC specimens respectively and the high relationship was also found (R^2: 0.90, 0.81 and 0.91) between splitting tensile strength and fracture energy for plain GPC, SF reinforced GPC and PPF reinforced GPC specimens respectively.

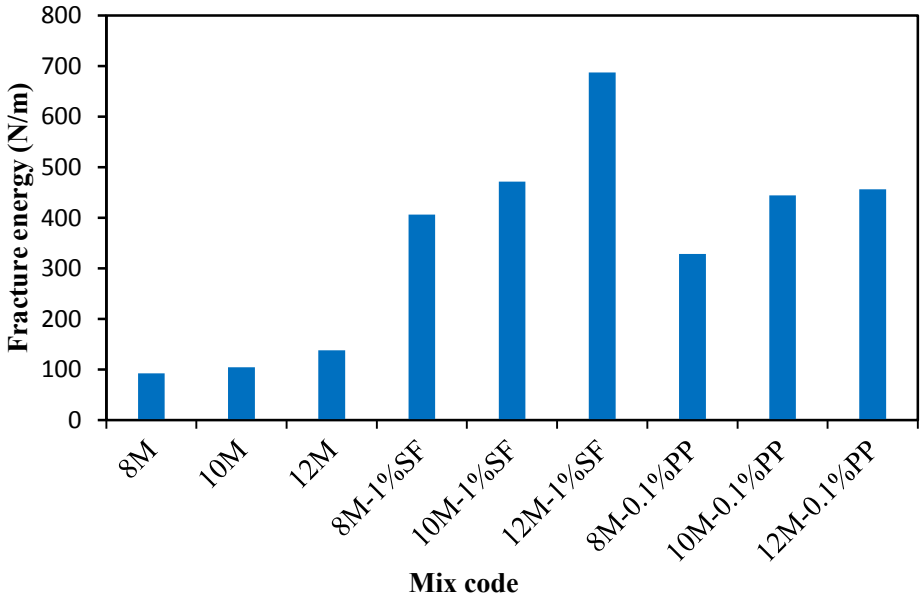
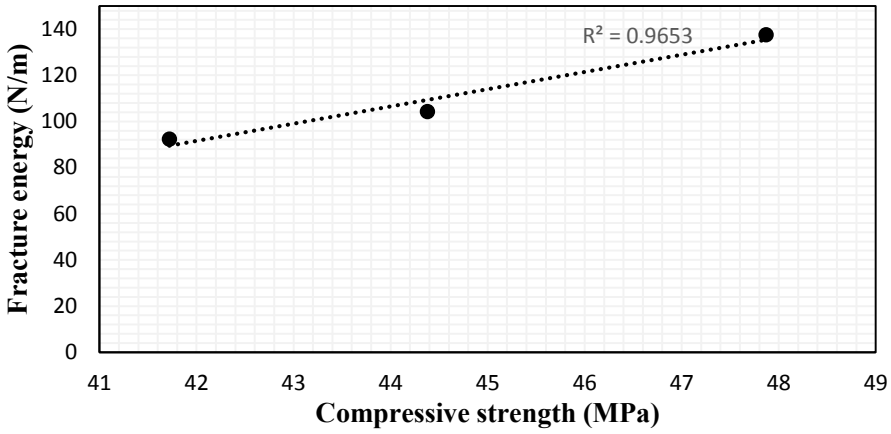


Figure 4.8 The fracture energy for plain and fiber reinforced GPC



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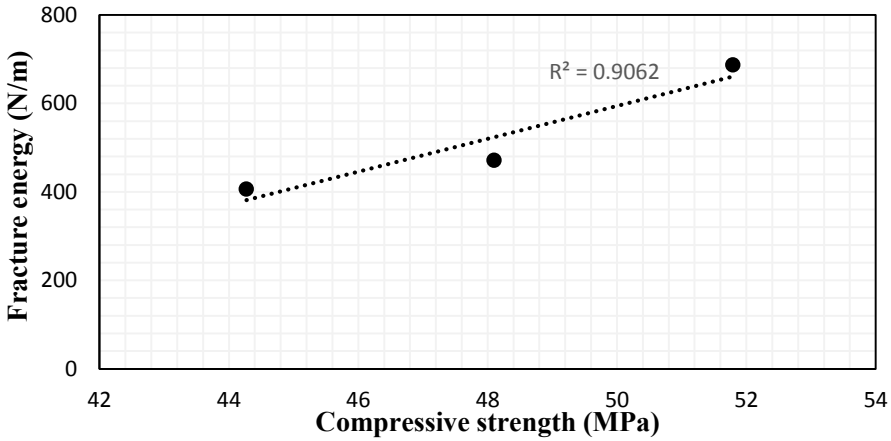

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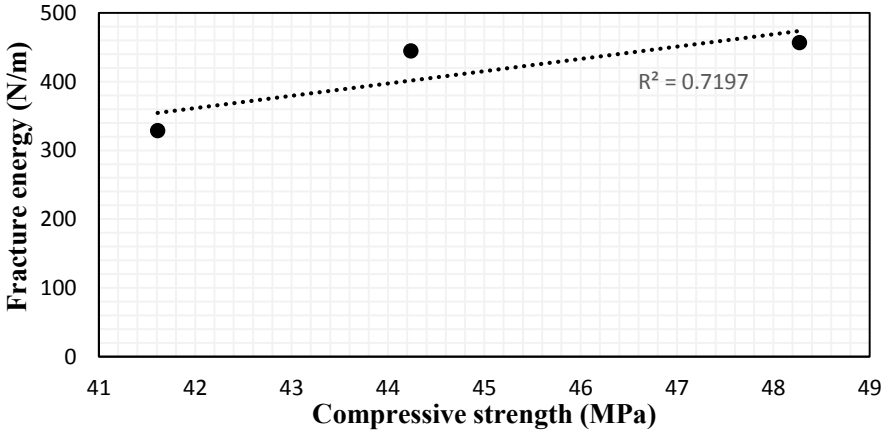
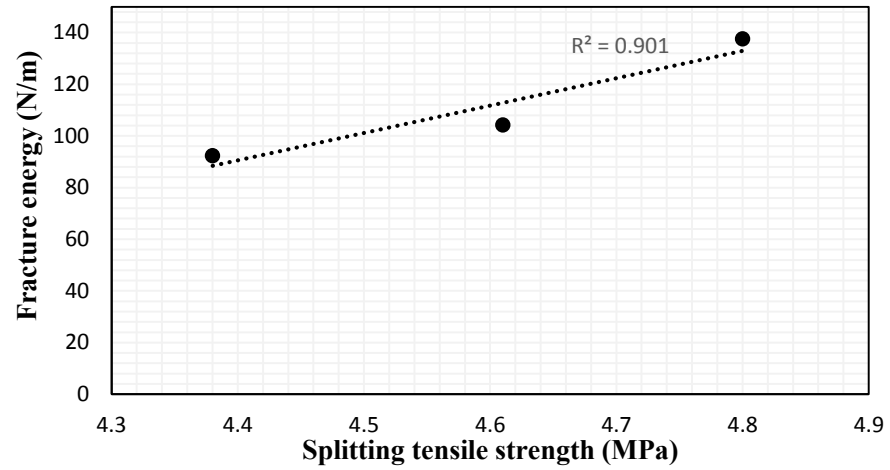
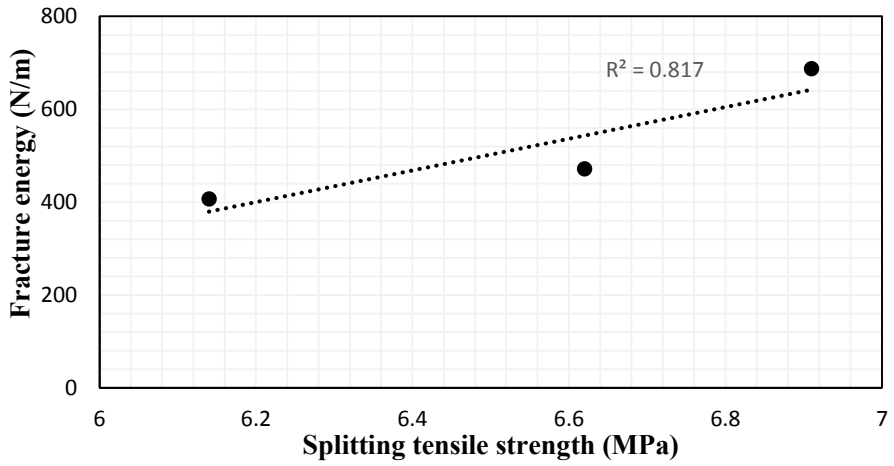


(c)

Figure 4.9 The relationship between fracture energy and compressive strength (a) Control mix, (b) with SF and (c) with PPF



(a)



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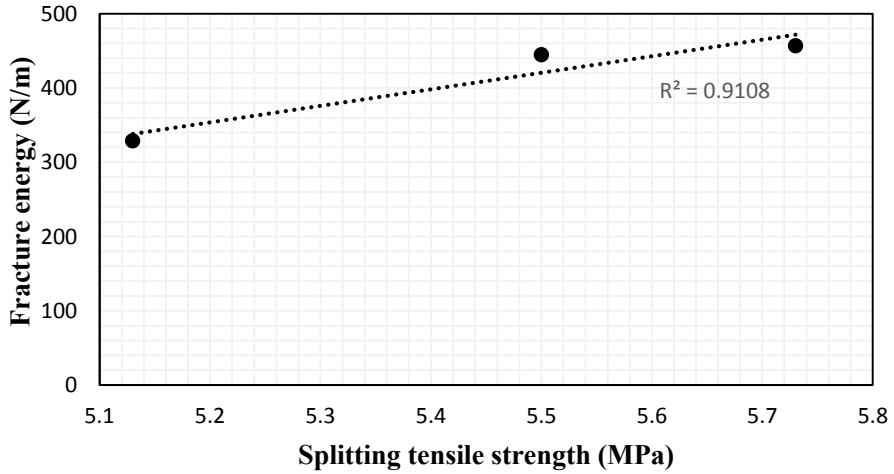


(c)

Figure 4.10 The relationship between fracture energy and compressive strength (a) Control mix, (b) with SF and (c) with PPF

4.6 Flexural Strength

The flexural and net flexural strength of plain and fiber reinforced GPC at 56 days are indicated in Figure 4.11and 4.12 respectively and summarized in Table 4.4. The flexural and net flexural strength was calculated using Eq. (3.3) and Eq. (3.4) which presented in section 3.6.3 respectively. As seen in Table 4.4 the flexural strength of plain GPC fiber reinforced GPC samples was increased with an increase of applied load, the flexural strength of plain GPC of the mixes 8M-0SF-0PP, 10M-0SF-0PP and 12M-0SF-0PP were found 1.25, 1.36 and 1.46 MPa respectively. The addition of SF increases both flexural and net flexural strength, the addition of 1% of SF improved the flexural strength of 8M, 10M and 12M by 12%, 9.55%, and 10.27% respectively. The incorporation of 0.1% of PPF in geopolymer mixture had a slightly increasing on the flexural and net flexural strength of GPC as seen in Figure 4.11 and 4.12.). A good relationship between compressive strength and flexural strength was observed (R^2: 0.956) for plain GPC and fiber reinforced GPC specimens and a relationship was also found (R^2: 0.950) between net flexural strength and compressive strength.

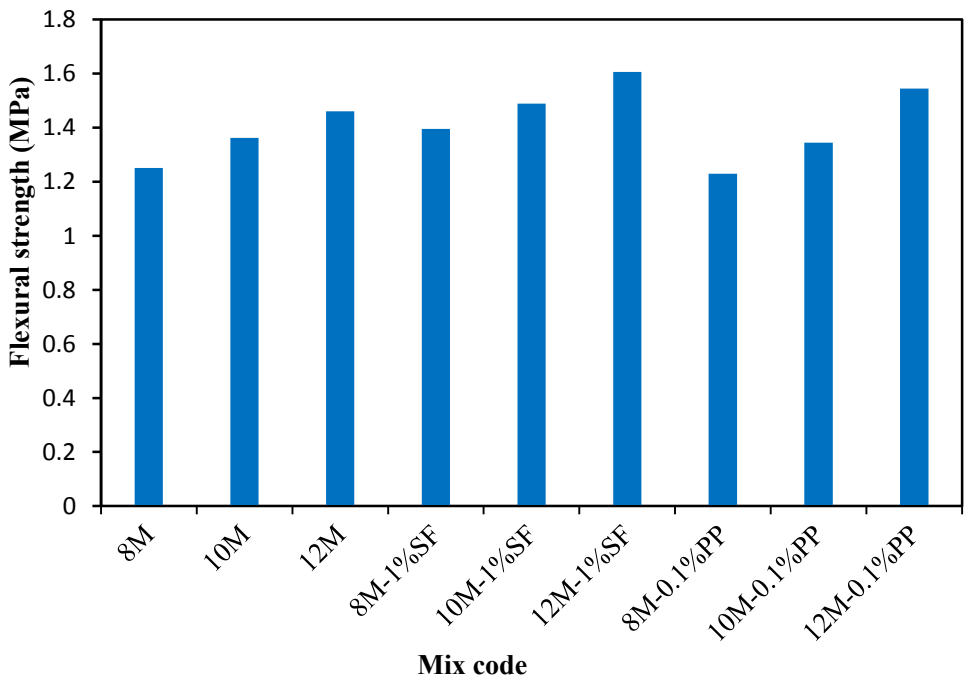


Figure 4.11 The flexural strength change of plain and fiber reinforced GPC

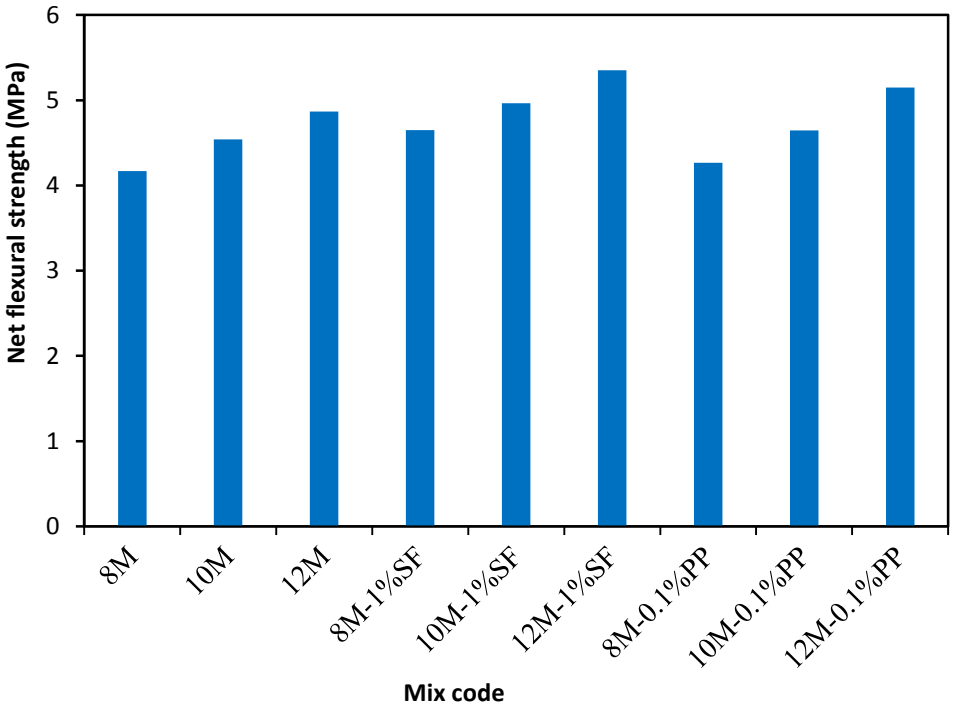
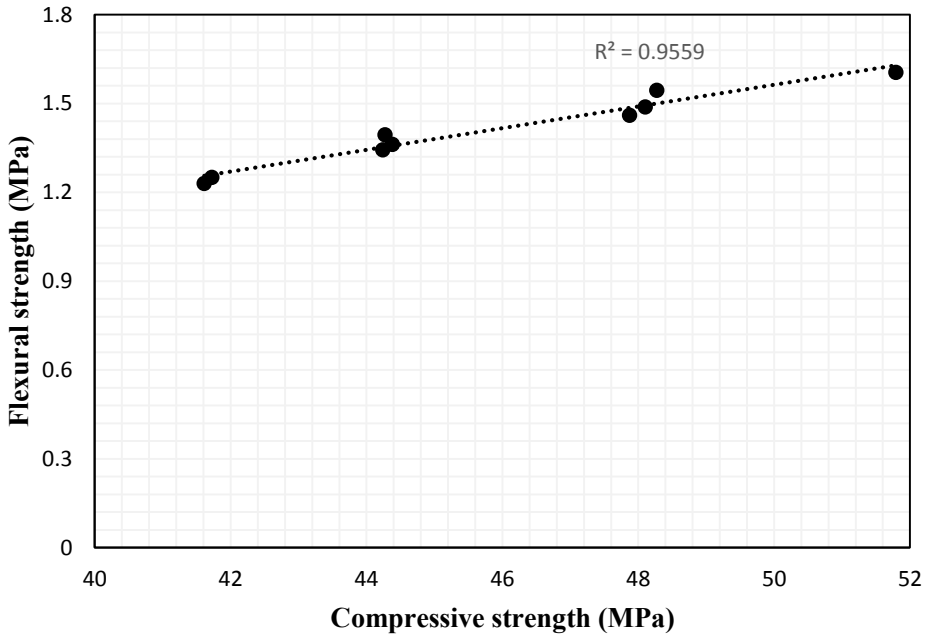
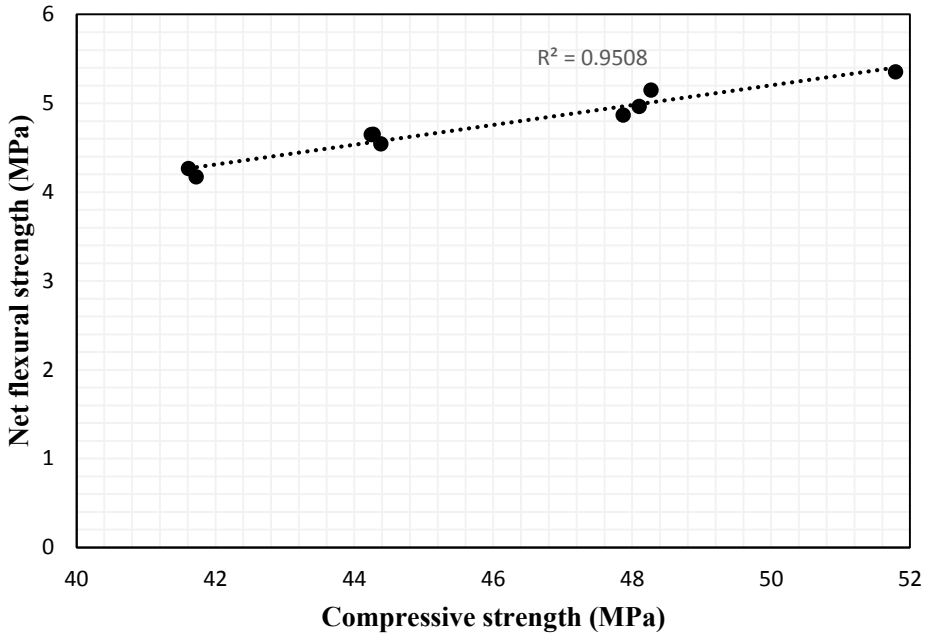


Figure 4.12 The net flexural strength change of plain and fiber reinforced GPC



(a)



(b)

Figure 4.13 Mechanical strength relationships of the specimens under different parameters (a) Compressive vs flexural strength (b) Compressive vs net flexural strength

4.7 Critical Stress Intensity Factor

Critical stress intensity factor or fracture toughness (K_{IC}) refers to the amount of the stress concentration near the crack tip when the crack starts to propagate. Fracture toughness (K_{IC}) was calculated utilizing (Eq. 3.5) which presented in section 3.6.3. Figure 4.14 shows the critical intensity factor of plain GPC and fiber reinforced GPC, It can be shown from the figure that stress intensity varied for different mixtures. The compressive strength of the mixtures played a significant role in improving better fracture toughness parameters. The fracture toughness at the crack tip is governed by the tensile strength of GPC, which is also associated with peak load. As seen in the results, K_{IC} of plain GPC and fiber reinforced GPC showed the same trend of compressive strength fracture energy and flexural tensile strength improvement for all of the mixtures. Intensity factor versus compressive and splitting tensile strength relationships to observe the effect of mechanical strength to fracture properties of the FA/GGBFS based GPC and fiber reinforced GPC as given in Figure 4.15 and 4.16. Results revealed that the critical stress intensity factor of the samples was improved with an increase in both compressive and splitting tensile strengths. It was observed that good relationships existed between K_{IC} and compressive strength

(R^2: 0.95), and K_{IC} and splitting tensile strength (R^2: 0.99). A similar observation was also stated by Sarker et al. [69] that fracture energy of the heat cured FA based GPC specimens was increased with an increase in compressive strength. The impact of splitting tensile strength on critical stress intensity factor (K_{IC}) was found more significant than the effect of compressive strength.

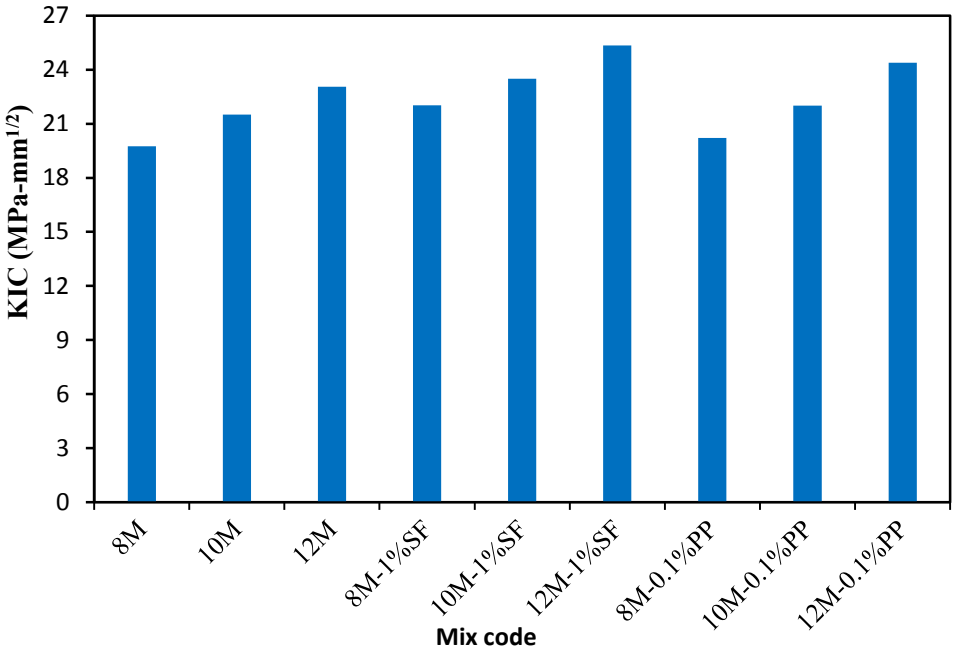
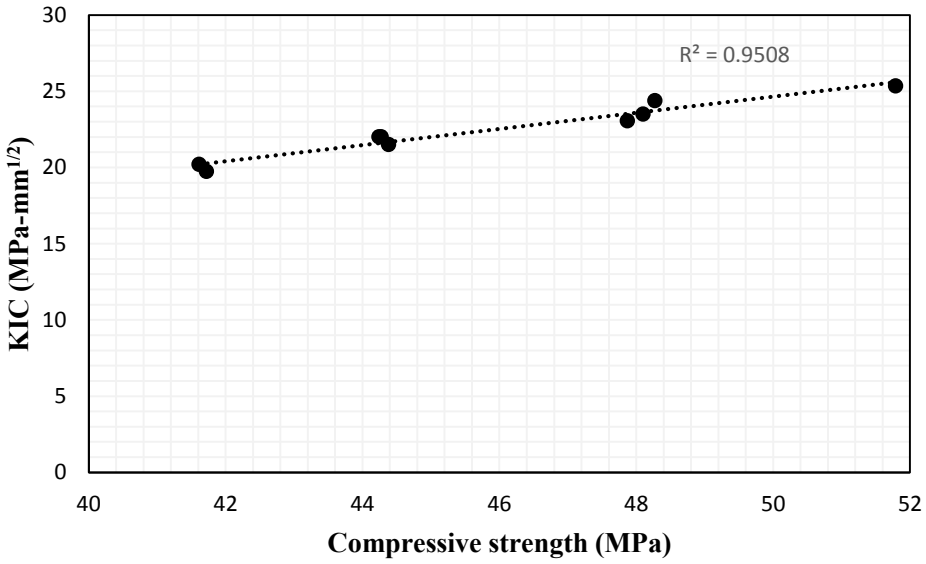
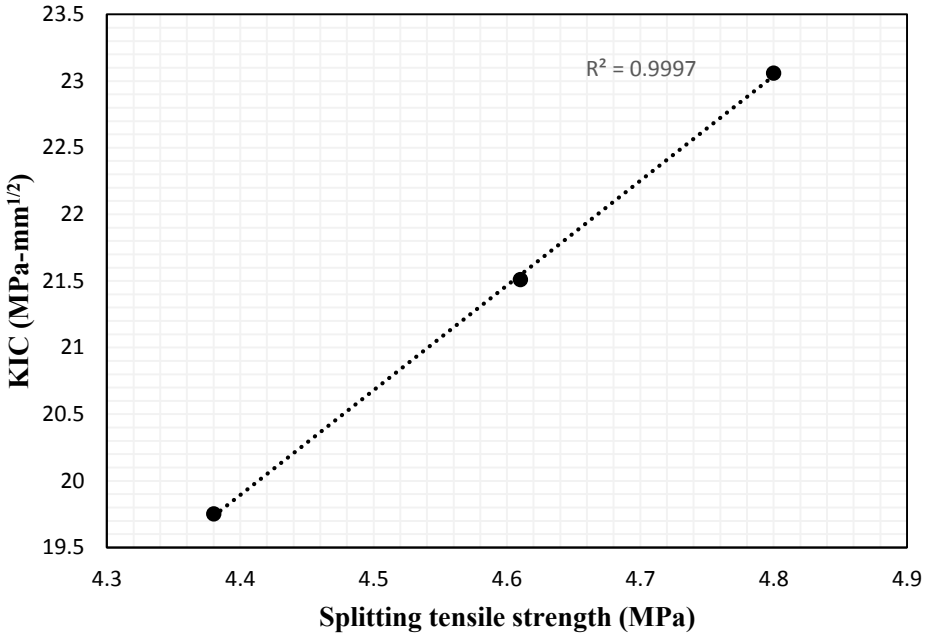


Figure 4.14 the stress intensity factor of plain and fiber reinforced GPC



(a)



(b)

Figure 4.15 Mechanical strength relationships of the specimens under different parameters (a) Compressive strength vs critical stress intensity factor (b) splitting tensile strength vs critical stress intensity factor

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The mechanical properties of FA / slag based GPC with and without fibers was investigated under curing temperature. The effect of different molarity of NaOH solution is also investigated. In addition to this, the applicability of GPC for structural use was also addressed. The following findings were summarized below;

- The geopolymer binder may be treated as alternative future eco- friendly to OPC in certain industrial applications.
- The result refers to a reduction in workability with the increase of molarity of GPC. Also, use the fibers had the adverse influence of GPC workability, and it was observed that the large effect of PPF on the workability. where the use of PPF reduced the workability of more than SF
- The increase in heat and time curing considerably enhanced the compressive, tensile, flexural strength, energy absorption capacity and post-cracking performance of plain and fiber reinforced GPC.
- It was observed that compressive strength did not vary largely with age. It was found that the curing temperature adopted is sufficient for completing the polymerization process and attaining the strength.
- Compressive, splitting tensile strength and fracture energy of GPC is also increased by increasing in the concentration of NaOH up to M12.
- The largest influence of SF is in the early ages more than late ages.
- According to the results, the PPF have not significantly affected in improving compressive strength compared to the control mix.

Incorporation of SF and PPF into FA / slag based GPC resulted in superior enhancement in the splitting tensile strength, flexural strength, area under the load-deflection curve and in the degree of fracture energy.

The using of the different molar concentration of NaOH observed to be less important in the behavior of fiber reinforced GPC.

5.2 Recommendation

The following recommendations are made for future work:

1. Investigation the durability properties of geopolymer concrete to evaluate the performance of the geopolymer concrete with a long time.
2. Study effect of the other curing methods as an ambient and/or steam on strength and durability of geopolymer concrete properties.
3. The environmental benefits of the replacement materials are well known, but the cost benefit remains unclear. The use of heat curing will increase the use of energy and CO_2 production. A detailed cost benefit analysis can be undertaken to determine the financial and environmental impact of the production of geopolymer concrete.

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