IOP Conference Series: Materials Science and Engineering

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To cite this article: M M A B Abdullah *et al* 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* **209** 012038

IOP Conf. Series: Materials Science and Engineering **209** (2017) 012038 doi:10.1088/1757-899X/209/1/012038

Performance and Characterization of Geopolymer Concrete Reinforced with Short Steel Fiber

M M A B Abdullah[1,2*], M A Faris[1,2], M F M Tahir[2], A A Kadir[3,2] , A V Sandu[2,4], N A A Mat Isa[1] and O Corbu[2,5]

[1]Faculty of Engineering Technology, Universiti Malaysia Perlis (UniMAP), Perlis, Malaysia

[2]Center of Excellence Geopolymer and Green Technology (CEGeoGTech), School of Materials Engineering, Universiti Malaysia Perlis (UniMAP), Perlis, Malaysia.

[3]Department of Water and Environmental Engineering, Faculty of Civil and Environmental Engineering, Universiti Tun Hussein Onn Malaysia, Johor, Malaysia

[4]Faculty of Materials Science and Engineering, Gheorghe Asachi Technical University of Iasi, Romania

[5] Central Laboratory of the Faculty of Civil Engineering, Technical University of Cluj Napoca, Romania

E-mail: mustafa_albakri@unimap.edu.my

Abstract. In the recent years, geopolymer concrete are reporting as the greener construction technology compared to conventional concrete that made up of ordinary Portland cement. Geopolymer concrete is an innovative construction material that utilized fly ash as one of waste material in coal combustion industry as a replacement for ordinary Portland cement in concrete. The uses of fly ash could reduce the carbon dioxide emission to the atmosphere, redundant of fly ash waste and costs compared to ordinary Portland cement concrete. However, the plain geopolymer concrete suffers from numerous drawbacks such as brittleness and low durability. Thus, in this study the addition of steel fiber is introduced in plain geopolymer concrete to improve its mechanical properties especially in compressive and flexural strength. Characterization of raw materials also determined by using chemical composition analysis. Short type of steel fiber is added to the mix in weight percent of 1 wt%, 3 wt%, 5 wt% and 7 wt% with fixed molarity of sodium hydroxide of 12M and solid to liquid ratio as 2.0. The addition of steel fiber showed the excellent improvement in the mechanical properties of geopolymer concrete that are determined by various methods available in the literature and compared with each other.

1. Introduction

Nowadays, the urge of using geopolymer concrete as green construction materials has increased parallel with infrastructure development besides increasing in awareness as a result of global warming. Therefore, the utilization of fly ash as waste material also improved and overcome a major problem for disposal [1]. However, plain cement concrete faced various imperfection such as brittleness, fracture resistance, and etc. [2]. Hence, the addition of steel fibres is an alternative to promote these problems such as toughness, flexural strength, and energy absorption improved.

Production of conventional concrete customarily used ordinary Portland cement (OPC) as the binder and the usage of OPC is on the increase to meet infrastructure developments [3]. However, the calcination of limestone and combustion of fossil fuels during the manufacturing of OPC resulting the huge amount of carbon dioxide, (CO_2) released to the environment [4]. Geopolymer is said to be a new alternative material which the greenness of conventional concrete is improved besides having a better performance compared to concrete with OPC. Plus, the production of geopolymer does not emit carbon dioxide to the environment thus overcoming the global warming issue [5].

According to findings reported by other researcher, the term geo-polymer referred covering class of synthetic alumino-silicate materials with potential use in a number of areas, essentially as replacement for Portland cement and for advanced high-tech composites, ceramic applications or as a form of cast stone [4]. Besides, as the chemical compositions of geopolymer materials are similar to natural zeolitic materials (but it has amorphous microstructure) geopolymer is considered as members of the family of inorganic polymers. The composition of zeolites is based on an aluminosilicate framework and a three-dimensional network of inorganic polymers that are made up of SiO_4 and AlO_4 tetrahedral that are linked by shared oxygen atoms into rings and cages [6].

In the present study, an experimental investigation on mechanical and physical performance of geopolymer concrete with addition of steel fiber has been carried out. Geopolymer concrete mixes were prepared with alkaline solution to fly ash ratio of 2.0 and short types of steel fiber is used with varying amount.

2. Materials and methods

Experimental work is designed to study the effect of addition short steel fibers on mechanical properties on geopolymer concrete. The main material used for making fly ash based geopolymer concrete composite specimen is fly ash along with other material such as coarse and fine aggregates, alkaline activator solution, steel fibers, and water.

2.1. Fly Ash

Low-calcium ASTM Class F dry fly ash obtained from local power station is used as the source material. In this experimental work, the fly ash used also from low-calcium ASTM Class F fly ash that is obtained from Manjung Power Plant, Lumut, Perak. With contains less than 10% of calcium oxide, Class F fly ash is suitable for geopolymer concrete production as it will makes substantial contributions to the workability, chemical resistance, and reduction in thermal cracking [2].

2.2. Alkaline Solution

The laboratory grade for sodium hydroxide (NaOH) is in the flakes form and sodium silicate (Na_2SiO_3) solution is used as alkaline activators. With about 98% purity, NaOH flakes is dissolved in water before it mixed together with the activator solution. The concentration of sodium hydroxide is fixed at 12M also the ratio of $NaOH/Na_2SiO_3$ at 2.5 as suggested by previous research [7].

2.3. Aggregates

The formulation of geopolymer concrete also need aggregates that consists of fine and coarse aggregates to occupy the largest volume about 75% to 80 % by mass. Available fine aggregates from river sand are used and the coarse aggregates came from crushed stones with nominal size of 5 mm and the maximum size is 20 mm. The ratio of fine and coarse aggregates are also included with fly ash ratio because they are considered solid constituent in the geopolymer concrete as fly ash/fine aggregates/coarse aggregates is 1:1:1.5 in ratio respectively.

2.4. Steel fibers

The steel fiber used in this study is short type of steel and with range of 0.03 mm to 0.06 mm length, which can make it sufficient to be randomly dispersed in geopolymer mixture. Short steel fibers is used with aspect weight ratio of 0 wt%, 1 wt%, 3 wt%, 5 wt%, and 7 wt%. The geopolymer concrete with no addition of steel fiber is used as a reference in this study.

2.5. Mix Proportion of Geopolymer Concrete

The mixing procedure used for this study is similar to conventional concrete and the process is done in the laboratory at room temperature. With ratio of 2.0 for solid to liquid ratio, fly ash and fine aggregates together with respective percentage of short steel fiber are initially mixed together [7]. Then the liquid component of the mixture is added to prepare wet mix until it gives homogenous mix. After that, the coarse aggregate is finally added to the mixture to ensure the homogeneity of mixture as well as to ease the mixing process. It is noted that, the mixture is quite faster to harden. Then, the mix proportion with respective fiber quantity is casted following the respective mold testing and finally cylindrical concrete molds were filled with geopolymer concrete mixture and the cured at ambient temperature.

Table 1. Quantity of fibers for various mixes.

Steel fiber (wt%)	GPC	GPC1	GPC3	GPC5	GPC7
Fiber quantity (kg/m^3)	0.0	26.0	78.0	130.0	182.0

3. Results and discussions

3.1. Chemical Composition Analysis

Table 2 presented the chemical composition of fly ash. Fly ash was obtained from Manjung Power Plant, Lumut, Perak and it was found to be corresponding to ASTM Class F with CaO content is less than 20%. The fly ash was used as the main constituent material for the production of geopolymer concrete.

Table 2. Chemical composition analysis of fly ash.

Component	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	SO_3	K_2O	MnO	BaO	SrO
Percentage (%)	38.80	14.70	19.48	1.02	18.10	3.30	1.50	1.79	0.16	0.27	0.11

Based on result, it is important to have higher percentage of SiO_2 in fly ash composition because silica is the main element of the structural skeleton for the reaction of product formed in the alkaline activation of fly ash. As reported by Feng, chemical composition of fly ash especially SiO_2, Al_2O_3 and Fe_2O_3 are important in order to establish a long-term pozzolanic activity in which fly ash reactivity with the lime (calcium hydroxide) in the chemical reaction [8]. Besides, these acidic oxide content (SiO_2, Al_2O_3 and Fe_2O_3) will resulting in widely range of strength activity index between 64 to 100%.

In addition, there are limits that should be acknowledge for the fly ash to be a leading construction material with optimal binding properties which are; the percentage of unburned material (LOI) should be lower than 5%, the content of Fe_2O_3 must not be higher than 10%, low CaO content and the amount of reactive silicate must be between 40% to 50% [9].

3.2. Analysis of Fresh Geopolymer

3.2.1. Workability. The trend graph shows the decreasing value of workability with increasing fiber content. The maximum slump value recorded is at 0 wt% of fiber content which is 100 mm and the lowest slump value recorded is 32 mm with the highest fiber content. Desirable workable flow is indeed important for workable and easily placed into the mold [10]. Besides, the workability of geopolymer mixture can be improved with addition of extra water and superplasticiser. However, superplasticiser contribute to negative impact on strength of geopolymer thus, it is preferable to have extra water rather than addition of superplasticiser.

There are several factors that can be affect the slump value of fresh geopolymer which are moisture content of aggregates, variation of ambient temperature, mixing time and degree of condensation reaction between binder and alkaline solution [11].

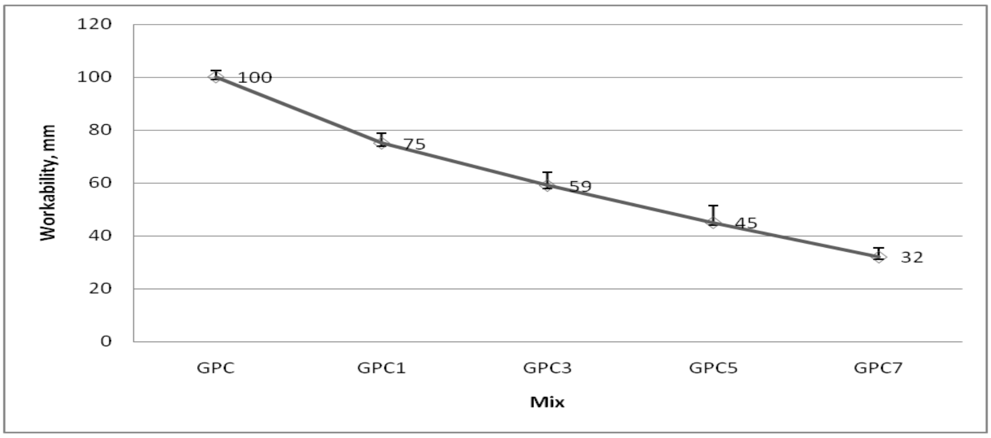

Figure 1. Workability of fresh geopolymer.

For this experimental work, if the fiber content is increases more than 7 wt% the compressive strength and flexural strength of geopolymer concrete is impossible to increases as the slump value continue to decrease. This will be difficulties for casting of geopolymer samples. Besides, the best workability of geopolymer according to The range of 100 mm to 175 mm and the lowest is below than 25 mm [12]. The workability of fresh geopolymer with addition of fiber which is the lowest workability is at the highest percentage of fiber content that is only 12 mm of slump value [13].

3.3. Physical Analysis of Geopolymer Concrete

3.3.1. Density. Figure 2 shows an increasing trend density of geopolymer concrete parallel to the increasing in volume of steel fiber in the mixture. The maximum density of the geopolymer concrete can reach up to 2500 kg/m^3 when the percentage of addition steel fiber is at 7 wt%.

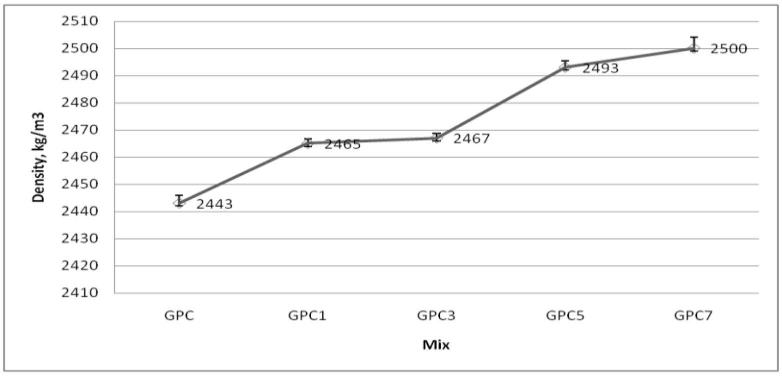

Figure 2. Density of geopolymer with addition of steel fiber.

However, GPC mix is recorded the lowest density of geopolymer concrete which is 2443 kg/m^3 when there is no steel fiber is added and considered to be reference point in this study. Besides, density of GPC1 with the lowest percentage inclusion of steel fiber is recorded higher than the reference mix which is 2465 kg/m^3.

3.3.2. Water Absorption. According to Luhar S., water absorption characteristic of geopolymer concrete contribute a large influence towards the durability of the structure [14]. Penetration of water into the geopolymer concrete will resulting the structure to become rubble thus, spalling concrete occurs. In the case of steel fiber reinforced concrete, this causes the steel bar embedded to corrode and finally reduces the life span of the concrete structure. The result in figure 3 also reveals that the water absorption of geopolymer concrete with addition of steel fiber is lower than the 0 wt% (control concrete) which is the lowest reading is at 7 wt% (2.7%). This shows that the concrete become less permeability to fluids (water) because of the pore is been occupied by addition of short steel fiber in the design of geopolymer concrete.

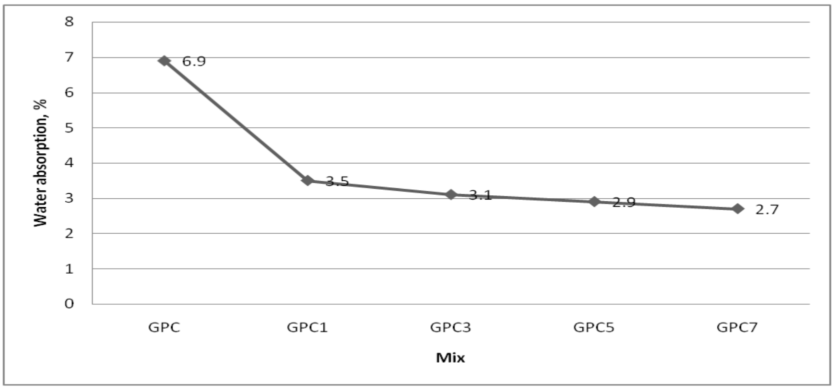

Figure 3. Water absorption of geopolymer concrete with various percentage of fiber.

Besides, if the permeability of geopolymer concrete tends to be high thus, the porosity also high due to interconnected in pores. Farhana stated that, as the concrete is a porous material it tends to have contact with surrounding environment and causing any movement of water through concrete structure hence gives an impact to the durability of mortar and concrete [15].

3.4. Mechanical Performance of Geopolymer Concrete

3.4.1. Compressive Strength. The results shown in the figure 4 are the average values of three specimens tested on the test age. Compressive strength of geopolymer concrete increases with respect to short steel fiber content in the mixture. The maximum increase in compressive strength is recorded when the percentage of short steel fiber is at the highest which is 69.80 MPa. Meanwhile, the lowest compressive strength is recorded at 1 wt% of addition steel fiber which is 45.40 MPa.

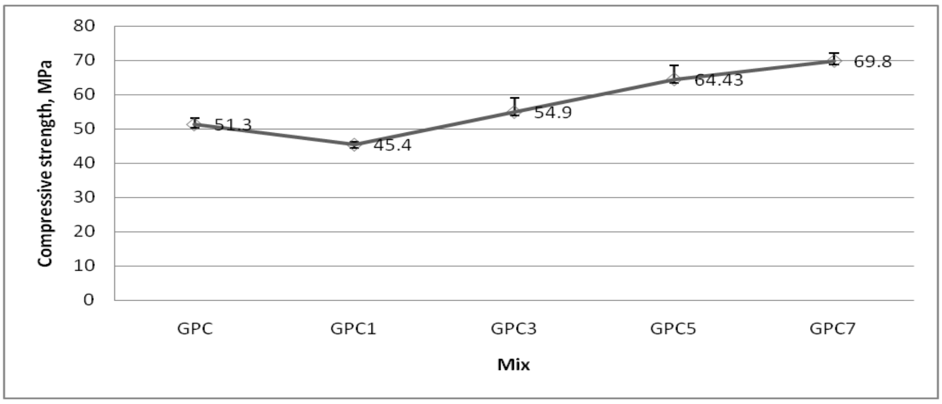

Figure 4. Compressive strength of geopolymer concrete with respect to various addition fiber content.

Based on the results, there are several reasons that may contribute to the value of compressive strength of all samples which can be divided into parameters to the compressive strength of geopolymer concrete; Firstly, the ratio of steel fiber content is very large, which exactly increases the compressive strength value of the geopolymer concrete as early as 14 days plus the value is considered higher than ordinary Portland cement concrete. Randomly and homogenous oriented steel fibers will arrest cracks formation and propagation when the concrete cracks thus, promote both ductility and strength of the geopolymer concrete [2]. Further mechanical performance of plain concrete have been enhance just through the expansion of fibers [16].

The bridging action is controlled by debonding, sliding and pulling out of fibers thus; the demand of energy for the crack to propagate is expanded. Hence, the optimum percentage of short steel fiber used in the production of geopolymer concrete is determined which is 7 wt% along with good mechanical performance of geopolymer concrete at its highest compressive strength of 69.80 MPa.

Next, as it can be seen in Figure 5, density of geopolymer concrete gives a direct relation towards the compressive strength of geopolymer concrete. This trend also similar with conventional concrete as increasing in curing time, the density of concrete also increased.

The increased in percentage of addition short steel fiber also one of the factors that increasing the density value the concrete.

The more compacted the concrete, resulting higher in compressive strength thus, to reduce the porosity of concrete, filler materials such as silica fume is added into the mix design of the concrete [17]. Meanwhile, in this case porosity of geopolymer concrete has been filled with aggregates and fly ash plus the inclusion of short steel fiber into the mixture.

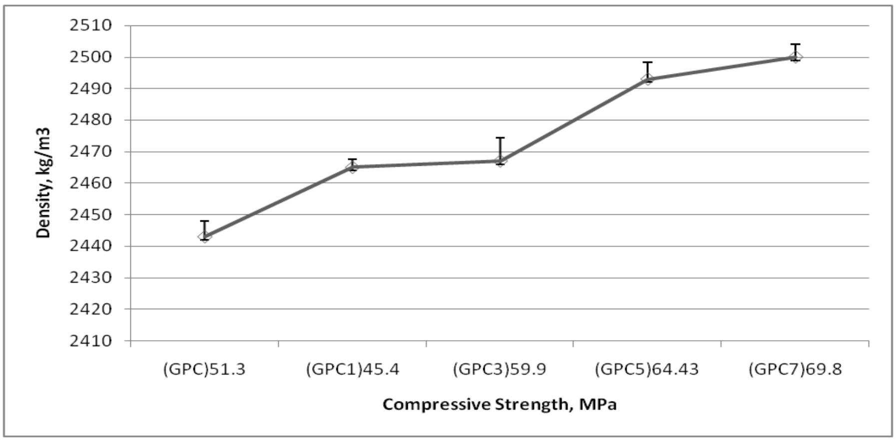

Figure 5. Density of geopolymer concrete against compressive strength.

Furthermore, to study the effect of curing age to compressive strength of geopolymer concrete reinforced with short steel fiber, the highest addition of steel fiber is chosen which is 7 wt% for the reason that it possessed the highest value of compressive strength which is up to 69.80 MPa.

As shown in the figure 6, the development compressive strength of geopolymer concrete is rising with longer curing age in which the value of compressive strength obtained is 4.1 MPa as early as 3 day. Meanwhile, the value of compressive strength continue to increase to 9.3 MPa, 13.7 MPa at the curing age of 5 day and 7 day respectively.

In addition, compressive strength of geopolymer concrete enhance by longer the curing time and curing at elevated temperature thus, promote geopolymerization process that resulting in higher compressive strength [18].

Despite the fact that reaction accelerate because of the heat, one must concern to minimize the loss of water [3]. However, geopolymer concrete experienced cracking as the negative response for curing at too high temperature thus, curing in temperature range of 60 °C to 90 °C within time in 24 hours to 72 hours is recommended by [6].

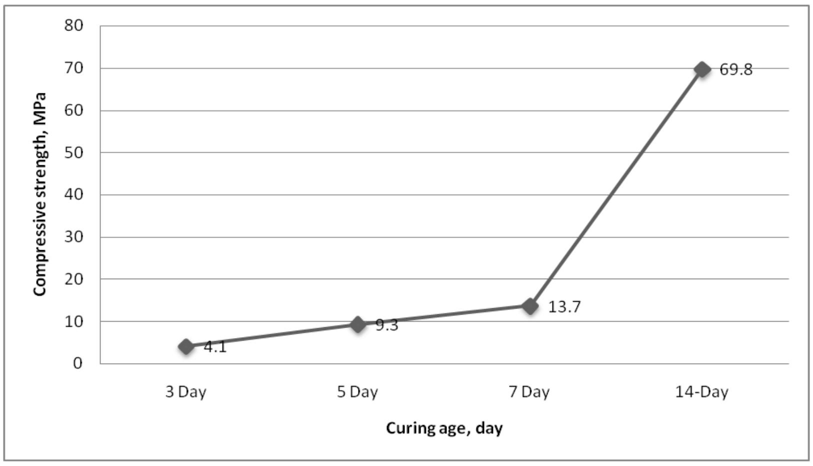

Figure 6. Compressive strength of geopolymer concrete for 7 wt% addition of short steel fiber with varying curing age.

3.4.2. Flexural Strength . Figure 7 shows the flexural strength results were plotted after 14 days of curing and the curing also takes place in ambient temperature same with compressive test samples. The increasing trending flexural strength for all samples is observed and the highest flexural strength value is up to 5.94 MPa at maximum fiber content which is 7 wt%. Meanwhile, the lowest fiber content in geopolymer concrete mixture has 1.45 MPa of flexural strength value.

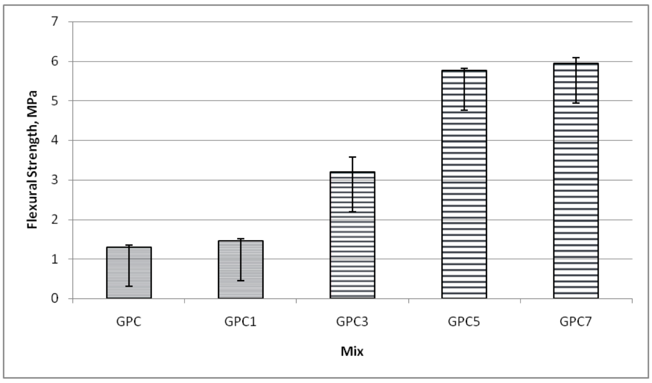

Figure 7. Flexural strength value for various percentage of steel fiber content.

Flexural strength value of geopolymer concrete indicates the durability characteristics of concrete structure hence determined the application of the concrete in many ways such as for railway sleepers, sewer pipes and also other precast concrete products. According to Llyod, by having an excellent early strength gain as a novel characteristic of geopolymer concrete can further exploited in precast industry where steam curing is used in order to increase the rate production of elements although curing in ambient temperature also possible [19]. Flexural strength of geopolymer concrete mix with addition of short steel fiber can decreases the crack propagation in concrete and attain higher peak value in terms of strength (include compressive strength). All the factors that contribute in higher value of flexural strength is the same as discussed in compressive strength results.

3.5. Relationship between Compressive Strength and Flexural Strength of Geopolymer Concrete

As discussed in compressive strength results there are several factors that contribute in order to obtained maximum value of strength included flexural strength which are; Firstly, the chemical composition of fly ash as raw materials itself that has less than 20% of CaO content by ASTM C 618 that can provide strength of geopolymer concrete. Besides, large amount of SiO_2, Al_2O_3 and Fe_2O_3 content contribute in the reactivity with lime element (Ca) in the chemical reaction to produce polymeric Si-O-Si bonds together with alkaline activator solution.

Next, the increasing trend shows in figure 5 density of geopolymer against compressive strength. It can be seen in that as density of geopolymer concrete continue to increase because of percentage of fiber content increase, therefore it also resulting the value of compressive strength increases. High amount of fiber content makes concrete become denser as it cover up large amount of pore in the concrete structure whereas strength of the concrete also maximize.

Besides, curing age of geopolymer concrete samples for both compressive and flexural strength also same (14 days) in ambient temperature. Therefore, the rate for polymerization process takes place is relatively low compare to when geopolymer concrete is cured in elevated temperature of range 60°C to 90°C as recommended by [6].

3.6. Morphology Analysis

All geopolymer concrete samples undergoes morphology analysis after mechanical testing (compressive test) is done. There are a few data that needed to be observed by doing morphology analysis such are to inspected cracks pattern on the concrete samples after been subjected to high load then to determine the effectiveness of fiber reinforced in geopolymer concrete structure.

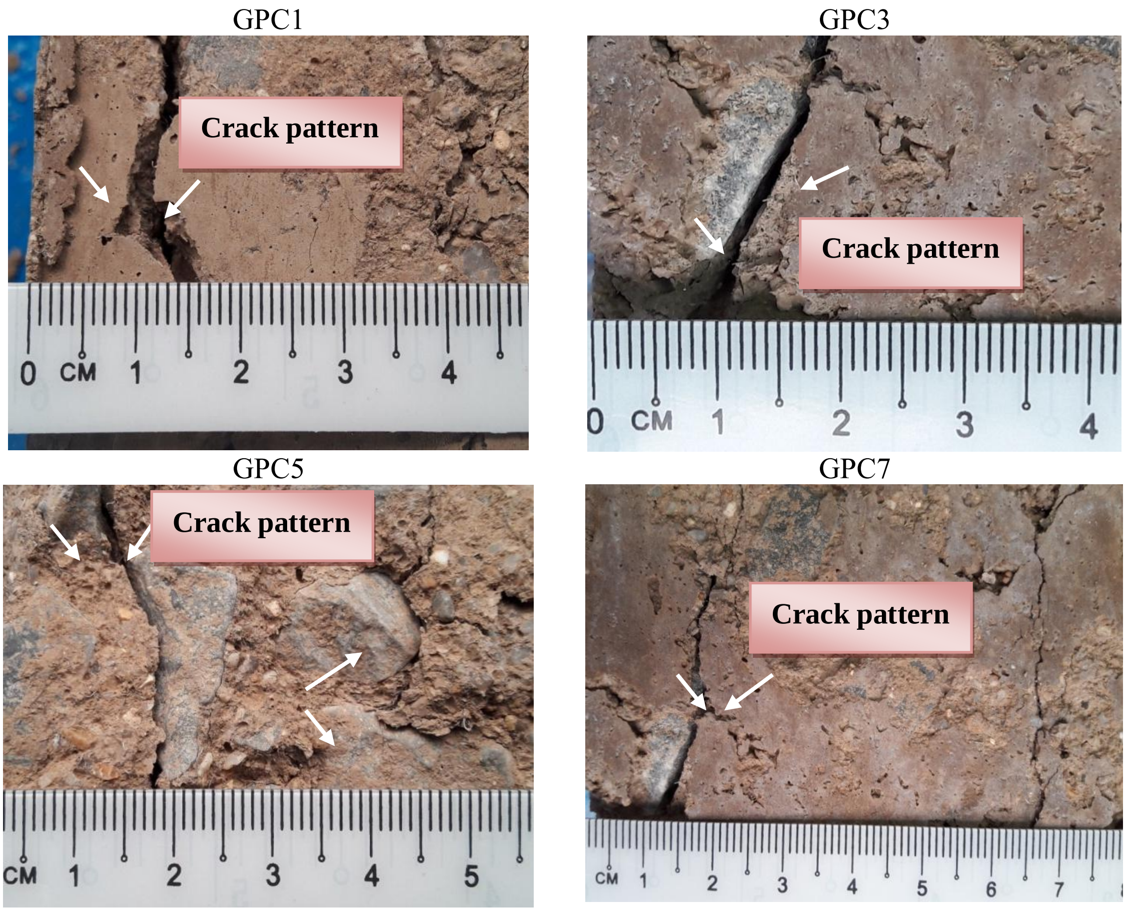

Figure 8. Crack patterns for geopolymer concrete structure after compressive strength testing.

As it can be seen in figure 8, as increasing in fiber content in geopolymer concrete smooth cracks surfaces are obtained. This indicates that maximum compressive strength of concrete is achieved as expected. Besides, the direction for cracks to propagates at all specimens is the same in which the cracks tends to avoid from bumping towards coarse aggregates in the concrete structure. Mix GPC specimen that have the lowest compressive strength value reveals that crack arresting did not happened as effective than other mix GPC1, GPC3, GPC5 and GPC7 because of there are no steel fiber content in the mixture. As mentioned before, plain concrete suffers major drawbacks such as brittleness and low elastic properties.

4. Conclusions

Based on the experimental results it is concluded that the density of geopolymer concrete increased with increase in fiber content, whereas both workability and water absorption results of geopolymer concrete reduced with increased in fiber content. The objective of this research is achieved when the optimum percentage of fiber content in geopolymer concrete structure is discovered. From the results obtained 7 wt% of short steel fiber content in geopolymer concrete structure shows maximum value of various strength which are compressive strength and flexural strength. The maximum value in compressive strength and flexural strength can achieved up to 69.80 MPa and 5.94 MPa respectively.

Eventually, these result display an excellent mechanical performance of geopolymer concrete thus accomplished another objective in this research which are the inclusion of steel fiber in mix design indeed contribute to good strength of the concrete structure. Besides, in order to prove geopolymer concrete to have better performance with addition of steel fiber as reinforced all samples are compared with control concrete (no steel fiber content). Therefore, both of research objectives are achieved.

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Acknowledgments
The author would like to express his gratitude to the Center of Excellence Geopolymer & Green Technology (CEGeoGTech) for funding the research project.