Al-Kerttani and Mutar *Journal of Engineering and Applied Science* (2021) 68:14
https://doi.org/10.1186/s44147-021-00013-z

Journal of Engineering and Applied Science

RESEARCH Open Access

Studying the behavior of geopolymer concretes under repeated loadings

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Abstract

This article investigates utilization of polypropylene microfibers as reinforcement in geopolymer concrete to enhance the ductility characteristics since the geopolymer concrete is considered a brittle material. The polypropylene microfibers were added to geopolymer concrete at the fiber volume content of 0.5%, 1.0%, and 1.5%. In this article, a slump test and compressive strength were tested for geopolymer concretes to measure the effect of polypropylene microfibers on geopolymer concretes. Also, static flexural strength and dynamic loading were applied to find out the attitude of polypropylene fiber-reinforced geopolymer concrete and to measure both the deflection and number of load cycles until failure. While comparing the results with reference geopolymer concrete, all samples were tested at 28 days and, finally, a statistical test was carried out. The results concluded that the use of polypropylene microfibers improves the compressive strength and enhances the properties of polypropylene fiber-reinforced geopolymer concretes, increases the loading for the appearance of the first crack, and decreases the deflection of polypropylene fiber-reinforced geopolymer concretes compared with reference geopolymer concrete.

Keywords: Deflection, First crack, Flexural strength, Geopolymer, Polypropylene fiber

Introduction

Sustainable growth in construction includes the following: using innovative materials and reusing waste and nonconventional materials to preserve raw materials and discover alternate methods for environmental preservation [1].

Geopolymers are minerals, usually ceramic, materials that form long-range, covalently bonded, non-crystalline (amorphous) networks. The characteristics and use of geopolymers are being surveyed in many industrial and scientific specifications such as geology, colloid chemistry, modern inorganic chemistry, mineralogy, and physical chemistry and in other applications of engineering procedures techniques. The field of geopolymers is a division of polymer science, technology, and chemistry that sort as a part of the basic rules of materials science [2].

Kim et al. [3] showed that geopolymers can be divided into two basic groups: pure mineral geopolymers and organic ones, which contain geopolymers, artificial analogs of naturally occurring macromolecules.

Normal concrete which was manufactured by Portland cement can be replaced by geopolymer concrete (GPC) since it is an environmentally friendly component and unparalleled sustainable to substitute [4]. A lot of materials can be used to make geopolymer, such as alumina-silicate materials (source fly ash (FA) and slag which are by-product materials also and geological materials origin such as metakaolin (MK) [5] considered as source materials. The productions of these pozzolanic materials produces less CO_2 and energy compared with the manufacture of Portland cement.

So, for preserving the environment to make it free from pollution and sustainability of raw materials, making of concrete using geopolymers as the binder has drawn the attention of many researchers [6]. The combination of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) is the major alkaline solution used in geopolymerization [7–10].

The combination of fiber with the brittle matrix is an effective method to enhance flexural strength and toughening mechanisms since it eliminates the crack development under various loading and environmental effects such as shrinkage [11, 12].

In contrast to most ceramics, a large domain of fibers, consisting of organics, can be utilized as reinforcement in the geopolymer due to the temperature of the geopolymers being close to ambient temperature [13]. Polypropylene (PP) was first utilized as reinforcement for concretes, to enhance their flexural strength. Thus, tests were also made to utilize it to reinforce composites based on geopolymers. So, PP fibers were a major of the first fibers which were added to geopolymers [12, 14, 15]. Therefore, Zhang et al. found that the early flexural strength of the composite which contain 0.75% polypropylene fiber (PPF) was improved about two times after 1and 3 days [16].

Zhu et al. [17] wrote an article with the utilization of fly ash-based geopolymers with 1.5% PPF by volume (length of 30 mm and 1 mm in diameter). The specimens were subjected to a high temperature 85° C for 10 h. The results showed that there was an improvement in mechanical properties. The compressive strength of the PPF composites was 91.7 MPa compared with 70 MPa for the matrix, while the results clarified the flexural strength were respectively 8.4 MPa for the composite and 7.1 MPa for the matrix material. Meanwhile, Zhu et al. tested the tensile strength, and there was an enhancement from 3.1 MPa for the matrix material to 6.4 MPa for the composite with PPF.

This kind of composite can be used as fireproof barriers in buildings since it has an excellent immovability against cracking at higher temperatures [8, 18]. Also, isolation and lightweight construction materials could be used this type of material [18].

Wang et al. [18] have investigated foamed geopolymers reinforced by PPF with fly ash. Fibers were with a diameter of 0.017 mm and length between 3 and 19 mm, and the volume of fibers added was 0.5%, 1.0%, 1.5%, and 2.0%. The superior indications were done for 0.5% PPF. The increment in compressive strength of fiber-reinforced composites with 3, 6, 9, 12, and 19 mm lengths compared to reference mixes was 57%, 46%, 57%, 71%, and 6% respectively.

Pham et al. [19] reached better results for mechanical properties when tested two lengths of PPF with 50 μm in diameter and lengths of 10 and 15 mm. PPF was added in amount of 0.5, 1.0, and 1.5% by volume to geopolymer matrix based on fly ash. The values showed enhancement in compressive strengths in addition to flexural strengths for both PPF lengths. The best values were reached for shorter PPF of 10 mm lengths. The compressive strength of 0.5% PPF was 43.3 MPa compared with 32.0 MPa for normal matrix, while the flexural strength had 8.0 MPa with a 1.5% PPF compared to 5.9 MPa for conventional concrete.

Behforouz et al. [20] tested geopolymers based on metakaolin with aggregates were reinforced by PPF of diameter 20 μm and length 6 mm. The PPF were put in the mix at 0.3, 0.5, and 1.0% by mass. The values did not show a difference in compressive strength; the strength of the reference specimen was 52.6 MPa compared to 53.1 MPa with 1% PPF. On the other hand, the flexural strength increases from 3.6 MPa for control mixes to 3.8, 4.2, and 4.9 MPa when 0.3%, 0.5%, and 1.0% PPF were added; same results were made by Yuan et al. [21].

Because of thermal insulation and lightweight of PPF, it is considered as most commonly used between different kinds of fibers [22–24] and also due to the advantages of PPF such as resistance to high temperature which reached 900° C and high resistance to aggressiveness of environment [25].

Methods

Research motivation

There are a lot of articles published dealing with geopolymer concretes characteristics such as mechanical properties and applications of this new type of concretes. Thus, the goal of this study is to find out the dynamic properties of PPFGPC under repeated loading and the deflection of PPFGPC when subjected to static and repeated loading when reinforced with 0.5, 1.0, and 1.5% by volume in addition to reference mix. For this, four mixes were mixed to test the slump flow in the fresh state of PPFGPCs, and then 12 cubes of 10 × 10 × 10 cm and 18 slabs with 40 × 40 × 5 cm were cast and classified into two groups, the first group which includes 0.0 and 0.5%. PPF investigated the ability of slabs to withstand the repeated loading until failure and the deflection during this recycling loading. In the second group, which consists of 0.0, 0.5, 1.0, and 1.5% PPF, the deflection during flexural strength until failure was tested and the load of the first cracks in both groups was observed. After that, the statistical test was carried out according to the ANOVA test.

Materials

In this work, the source of materials used was metakaolin MK which is conformed to ASTM C 618 [26]. The chemical composition and physical properties of MK are shown in Table 1. In this work, the alkaline solution used was NaOH and Na_2SiO_3 liquids. The mass ratio of NaOH to Na_2SiO_3 solution used was 0.4 is used. The lucidity of NaOH which is available in the state of pellet is 99%; the solution consisting of NaOH and water gave a concentration of 14 M.

The fine aggregate used is Al-Ekhadir natural sand which, passing from the sieve 1.18 mm, has a specific gravity of 2.6 and a broken natural coarse aggregate with 10 mm maximum size with a specific gravity of 2.7. Also, the superplasticizer (SP) type F in accordance to ASTM C494-19 [27] was used to reach the required workability. The

Table 1 Chemical analysis and physical properties of metakaolin

Oxides	Content%
SiO_2	54.2
Al_2O_3	39.00
Fe_2O_3	0.92
CaO	1.37
MgO	0.15
SO_3	0.45
Na_2O	0.22
K_2O	0.27
LOI	0.71
TiO_2	0.8
Physical properties	
Physical form	Powder
Color	Off-white
Specific gravity	2.64
Surface area, m^2/g	13.3

characteristics of polypropylene microfibers utilized in this investigation were specified by the industrialist as shown in Table 2.

Mix design

Geopolymer concrete mix proportion, which was considered in this work, was constantly mixed and, depending on Al-Shathr. et al [29], mixed with 0.0, 0.5, 1.0, and 1.5% PPF as shown in Table 3, while Table 4 illustrates the description of each mix and the method of applied loading.

Mixing, casting, and curing of samples

The procedure which was designed for mixing GPC mixes was as follows: first, mix the dry component (MK, sand, and gravel) added progressively to the pan of mixer while the mixer was in rotary state for 2 min at low speed. Then, 65% of water and alkaline liquid with superplasticizer were added, whereas the mixer was at low speed, and then the PPF was added. Finally, the residual amount of water and alkaline liquid with superplasticizer was added, increasing the speed of the mixer for 2 min.

Table 2 Properties of PPF

Chemical base	100% polypropylene
Appearance/color	Transparent fibers
Density	0.91 g/cm^3
Dimensions	Diameter 32 μm
	Length 12 mm
Product declaration	Class 1a: mono-filament (EN 14889-2) [28]
Melting point	160 °C
Specific tensile strength	~ 30 cN/tex

Table 3 Mix properties of geopolymer concrete

Metakaolin (MK) (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	Alkaline solution (lit/m^3)	Water (lit/m^3)	SP % (from metakaolin volume)
400	720	1100	180	40	3

Vibrating table was used to consolidate the green concretes after being poured into the molds, and the molds were subjected to direct sunlight after demolding for 28 days as shown in Fig. 1.

Results and discussions

Slump test

The slump test was done according to ASTM C143-10a [30] on fresh mixes of geopolymer concrete immediately after mixing. The slump test results are illustrated in Fig. 2.

From Fig. 2, it can be concluded that the addition of PFF to GPC decreases the slump of concretes. The slump decreases from 3.5 cm of S1 to 2.8 cm for S5; this behavior of concretes was expected since the addition of fiber in general makes the concretes harsh and stiff which reduces its workability; these results conformed to the results of Ranjbar et al. [31].

Compressive strength

The compressive strength test was done according to BS EN 12390-3:2002 [32]. Three cubes with dimensions of 10 × 10 × 10 cm for each mixture were tested using a 2000 kN hydraulic compressor at the age of 28 days.

From Table 5, the compressive strength of GPCs in general enhanced with the addition of PPF increases with the increase of PPF to 0.5% and reached 34.7 MPa compared to 31.2 MPa for reference GPCs. But, after that, it starts reducing. These results conform to the results of Pham et al. [19].

First crack load

The central deflection was measured at the center of the panels (40 × 40 × 5) cm, by using dial gage of 0.01 mm accuracy with 25 mm capacity as shown in Fig. 3.

The first crack load means the load at which the first crack is created. The first crack load of all the GPC samples is illustrated in Table 6. For S2, the deflection is 8.235% lesser than S1 at the same first crack load. On the other hand, for S3, the deflection was less than S1 by 5.882% but with 25% increase in the first crack load, while for S5,

Table 4 Specimen nomenclature and description

Specimen ID	Description
S1	Reference GPC subjected to flexural strength
S2	Reference GPC subjected to repeated loading
S3	0.5% PPFGPC subjected to flexural strength
S4	1.0% PPFGPC subjected to flexural strength
S5	1.5% PPFGPC subjected to flexural strength
S6	0.5% PPFGPC subjected to repeated loading

Fig. 1 Mixing, casting, and preparing to test of PPFGPCs

the first crack load increased by 50%. It can be noticed that the fiber-reinforced geopolymer concretes have 50% more load-bearing capacity than GPC samples at the first crack load; these results matched with the conclusions of Nath [33]. Pham et al. [19] tested the GPC reinforced with 0.5, 1.0, and 1.5% volume fraction of PPF with SEM (Scanning Electron Microscopy) test; they concluded that the adhesion between PPF and base materials was excellent also; the paste around PPF was denser and improved compared to reference GPCs.

Ultimate load

The ultimate load is the maximum load-bearing capacity of the samples before failure. Table 6 shows the ultimate load of all panels. From Table 6, the deflection decreases from 11.5 mm for S1 to 8.0 mm in S5, while the volume of PPF increases (i.e., it decreases by 30.435%), and the ultimate load was increased from 11 kN in S1 to 16 kN in S5 (the percentage increase was 45.45%). This behavior may be attributed to the presence of PPF, as shown in Fig. 4.

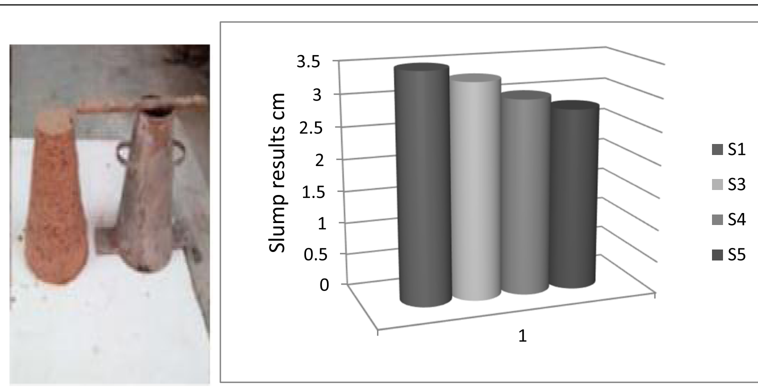

Fig. 2 Relationship between slump of GPCs and addition ratio of PPF

Table 5 Compressive strength of GPC with and without PPF

% of volume fraction of fiber	Compressive strength MPa
0.0	31.2
0.5	34.7
1.0	33.5
1.5	32.3

Hysteresis behavior

The deflection of the samples at each increment and decrement of the load was studied in the load control technique. 1.0 kN load interval was used in the test to produce hysteresis loops of the samples. The hysteresis loop clearly defines the yield-deformation and maximum deformation of the specimen due to applied loading. The typical hysteresis loop behavior of normal GPC (S2) and GPCs with 0.5% of PPF (S6) at the 1st, 2nd, and 3rd loop are shown in Figs. 5, 6, 7, and 8.

From Figs. 5, 6, 7, and 8, it can be noticed that S6 have higher ultimate load (7 kN) and less deflection (10.5 mm at failure (cycle 3)) compared to S2 which have 6 kN ultimate load and 12 mm deflection; also, the first cracking load was 4 kN for both mixes at 1st cycle with 0.84 and 0.80 mm deflection at first crack load. From Figs. 2 and 3, the differences between deflection when increasing loading and decreasing it approximately equals along the cycle for S6 can be seen, while for S2, the differences are decreasing gradually. These behaviors may be attributed to existing PPF.

Statistical test

In this work with a view to detect the statistical value of the experimental work variables in a quantitative method, general linear model analysis of difference

Fig. 3 Dial gage of 0.01 mm accuracy

Table 6 Deflection at first crack load and ultimate load of samples

Sample ID	First crack load (kN)	Deflection at first crack load (mm)	Ultimate load (kN)	Deflection at ultimate load (mm)
S1	4	0.85	11	11.5
S3	4	0.78	12	10.0
S4	5	0.8	15	9.15
S5	6	1.28	16	8.0

GLM-ANOVA was used 0.05 as a level of significance. GLM-ANOVA is a program assistance in decreasing the error differences and indicates the dominance of a control factor and is considered a significant statistical analysis and diagnostic tool. In the analysis, the measured deflection for PPFGPCs were appointed as the dependent variables while the volume fraction of PPF, first crack load, and ultimate load was chosen as the independent factors. GLM-ANOVA was used, and their percent contributions and the effective test parameters on the deflection results are shown in Table 7. The independent variable is accepted as a significant factor on the test results when the P value is less than 0.05. The degree of effectiveness of the independent factors on the measured property which is known as the percent contribution was also determined. When the effectiveness of that parameter on the

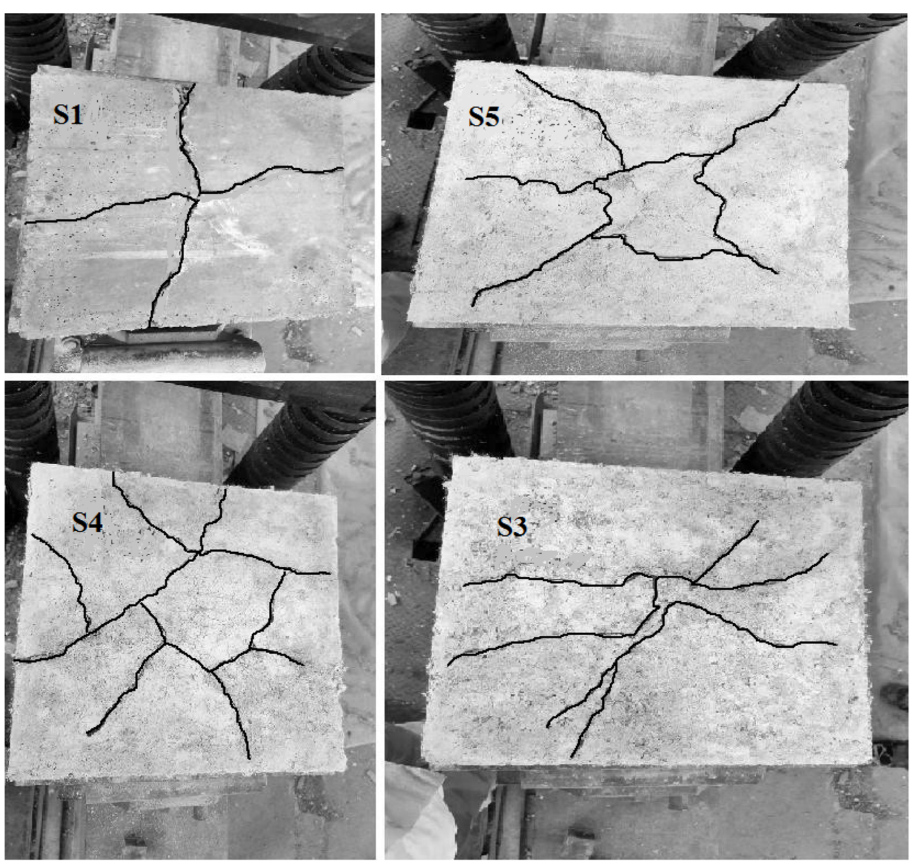

Fig. 4 Cracking patterns of different PPFGPCs

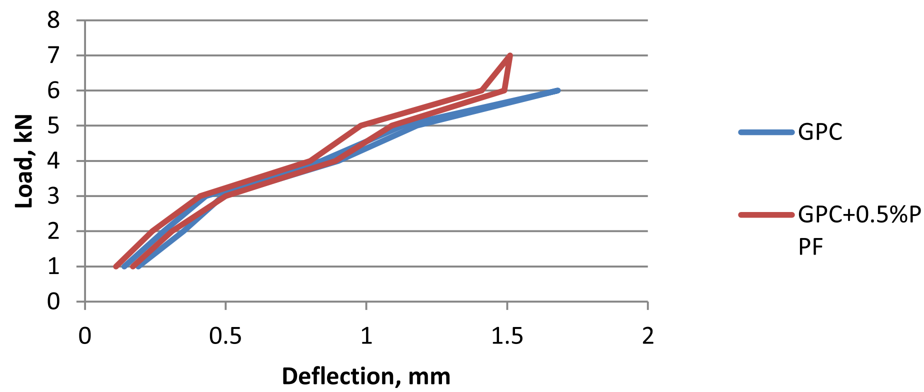

Fig. 5 First cycle for S2 and S6

measured property is higher, that leads to increase the percent contribution. Likewise, if the input of the factor to that certain reaction is less, that means the percent contribution is low. The statistical evaluation of the test results indicated that all independent variables had a remarkable effect on the deflection of the mixtures when P values of the independent variables were considered.

Conclusions

This study tested the deflection of metakaolin-based geopolymer reinforced by polypropylene fibers (PPF) under static and repeated flexural loading, in addition to slump test for fresh concretes and statistical test for the results. The following conclusions were noticed according to our experiments:

1- As the amount of fibers increases, the workability of the PPFGPCs decreases significantly due to the shear resistance to flow.
2- The compressive strength of GPC increases with 0.5% addition of PPF, but, after that, it started to reduce.

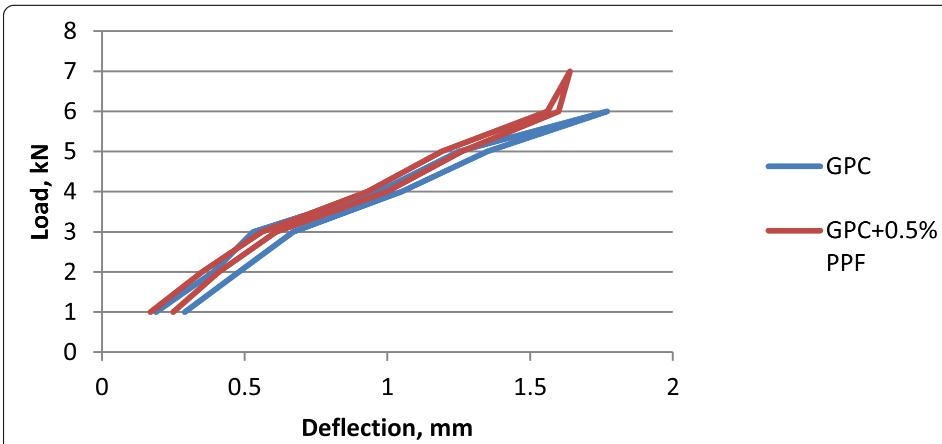

Fig. 6 Second cycle for S2 and S6

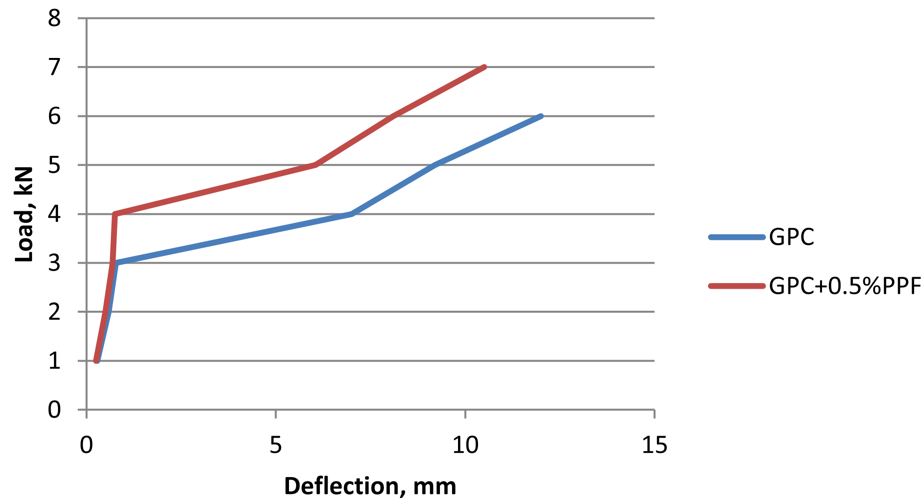

Fig. 7 Third cycle for S2 and S6

3- As the fiber percentage increases in the GPCs, the flexural strength increases compared to GPC without fiber; also, the load of the first crack increases as the amount of fiber increases.
4- The deflection of PPFGPCs decreases as the fiber content increases at the same load; this relation is applied for static and repeated flexural loading; this behavior leads to the enhanced energy absorption (flexural toughness) of the material.
5- The effect of PPF volume, first crack load, and ultimate load was statistically tested, and it was seen that all independent parameters, PPF volume, first crack load, and ultimate load, had a significant effect on the deflection of the PPFGPCs regarding to *P* values. However, the most effective independent parameter was the PPF volume according to percent contribution values.

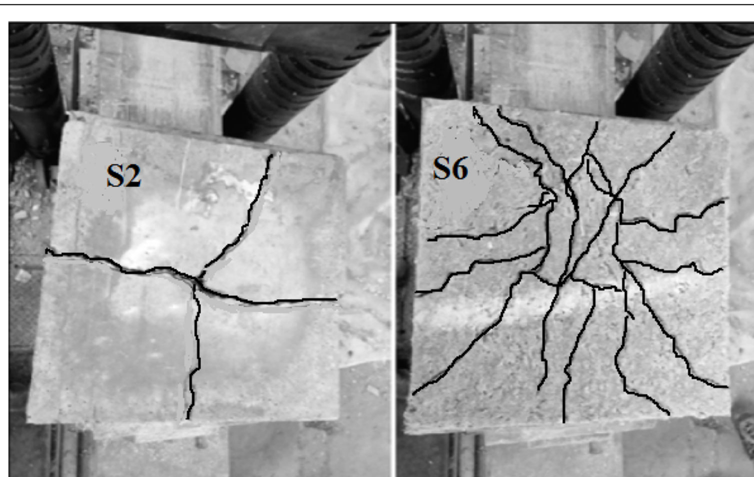

Fig. 8 Cracking patterns for S2 and S6 after 3 cycles of loading and unloading

Table 7 Statistical evaluation of deflection of PPFGPCs

Dependent variable	Independent variable	Sequential sum of squares	Computed F	R squares %	*P* value	Significance	Contribution %
Deflection	PPF volume	0.002773	113.7	90.8	0.01	Yes	45.6
	First crack load	0.001917	26.7		0.03	Yes	28.0
	Ultimate load	0.001117	15.3		0.02	Yes	19.9
	Error	0.000586	–				6.5
	Total	0.006392	–				–

Abbreviations

PPF: Polypropylene microfibers; GPC: Geopolymer concrete; PPFGPC: Polypropylene fiber-reinforced geopolymer concrete; FA: Fly ash; MK: Metakaolin; SP: Superplasticizer; ASTM: American Society for Testing and Materials

Acknowledgements

The authors would like to thank Al-Mustansiriyah University (www.uomustansiriyah.edu.iq) Baghdad-Iraq for its support in the present work.

Authors' contributions

The team cast the samples and examined them. AM analyzed the results, and OM wrote the manuscript. All researchers read the manuscript and approved it.

Funding

This study had no funding from any resource.

Availability of data and materials

All data and materials will be available upon request.

Declaration

Competing interests

There is no conflict of interest between the authors.

Received: 29 April 2021 Accepted: 2 August 2021
Published online: 14 October 2021

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