Tikrit Journal of Engineering Sciences

TJES Tikrit Journal of Engineering Sciences

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Assessment of Mechanical Performance of Fiber Reinforced Geopolymer Concrete at Different Curing Conditions

Alaa Y. Hussein*, Hammad M. Abd, Hasan M. Ahmed Albegmprli

Building and Construction Engineering Techniques, Technical Engineering College of Mosul, Northern Technical University, Iraq.

Emails:
Alaa Y. Hussein: alaa.yusife@ntu.edu.iq, Hammad M. Abd: hammad.munthir96@ntu.edu.iq, Hasan M. Ahmed Albegmprli: albegmprli@ntu.edu.iq

Abstract:
The building industry has made extensive use of types of concrete in recent decades. Geopolymer Concrete is one of several common types of concrete and does not require a water spray after casting. The research was limited to the use of industrial waste and waste harmful to disposal in structural technology. This paper investigates the effect of the curing type and hybrid fibers on the properties of reinforced geopolymer concrete. Binder materials for geopolymer mixes consist of 70% fly ash, 20% slag, and 10% cement. Four steel fiber proportions 0%, 0.5 %, 1 % and 1.5%, were studied in addition to mixing reinforced with hybrid steel fiber 0.5% and polyolefin fiber 0.5%. All geopolymer concrete specimens were cured at oven and ambient temperatures for 7, 28, and 56 days. The binder materials were activated with sodium silicate and sodium hydroxide solutions. Trial used the best ratio for an alkaline solution, which is assigned as Alkali Activators/Binder = 0.5, Sodium Silicate/Sodium Hydroxide = 1.5, and 14 Molarity. The mixture containing 1% steel fiber was selected and studied with a hybrid fiber. Hardened properties were tested using compressive strength, flexural strength, splitting tensile strength and modulus of elasticity. The results showed a difference between ambient and oven curing, with oven-cured specimens exhibiting higher compressive strength than ambient-cured specimens at early ages. At the same time, compressive strength was higher at late ages under ambient curing than under oven curing. Also, the other mechanical tests, splitting tensile strength, flexural strength and modulus of elasticity, exhibit the same as compressive strength in both curing conditions. The increase in compressive strength at 0.5%, 1%, and 1.5% steel fiber content at later ages was 20%, 33%, and 49%, respectively. As for the hybrid fiber mixture for Geopolymer Concrete, the increase in compressive strength was 24%. The addition of fibers in Geopolymer Concrete mixes did not affect the modulus of elasticity values. The results concluded that the geopolymer concrete exhibits an efficient performance in both ambient and oven curing. Consequently, it can be the best alternative to Ordinary Portland Cement concrete in site-cast without special curing conditions.

Keywords:
Geopolymer concrete; Fibers; Cementitious materials; Alkali activators; Cuing.

Highlights:
- GPC was considered sustainable concrete due to less harmful to the environment.
- The mechanical performance of GPC reinforced with SF and HF was tested.
- Superplasticizers (Hyperplast PC200 and Sika ViscoCrete®-5930) was done using and study the comparison between them.

Article History:

Received:	04 Nov. 2023
Received in revised form:	30 Jan. 2024
Accepted:	19 Apr. 2025
Final Proofreading:	21 Apr. 2026
Available online:	06 May 2026

https://doi.org/10.25130/tjes.33.1.13

Corresponding Author*:

Alaa Y. Hussein
Building and Construction Engineering Techniques, Technical Engineering College of Mosul, Northern Technical University, Iraq.
Email: alaa.yusife@ntu.edu.iq

Citation:
Hussein AY, Abd HM, Albegmprli HMA. **Assessment of Mechanical Performance of Fiber Reinforced Geopolymer Concrete at Different Curing Conditions**. *Tikrit Journal of Engineering Sciences* 2026; **33**(1): 1854.

1.INTRODUCTION

With the world's continued development, concrete has become the most common building material. As we know, cement is the binding material that holds the components of concrete together. In terms of environmental pollution, cement production is among the most hazardous industrial activities. The cement industry emits large amounts of carbon dioxide (CO_2) into the atmosphere, suggesting the need for low-emission alternatives. One alternative to carbon dioxide is Geopolymer concrete (GPC) [1, 2]. Geopolymer is an alternative to ordinary Portland cement (OPC); it is produced by partially replacing cement with industrial by-product materials rich in alumina and silica, such as slag, fly ash (FA) and metakaolin [3, 4]. FA has been identified as a key potential material for geopolymer production because it contains silica and alumina as major components. The researchers focused their studies on geopolymer manufactured from fly ash at the end of the last century, with an emphasis on different properties of mortar and paste samples [5]. The properties of geopolymer are significantly affected by the source of fly ash, its chemical composition, and the activator solution; these properties vary with the source [6]. GPC is chemically prepared using highly alkaline solutions (AS); it is a basic component of GPC [7] that activates the reaction between silicon and aluminium in the replacement or cementitious materials (CMs) [8]. The alkaline activators (AA) are a combination of liquid silicates and flakes or powder of hydroxides soluble in silicate. The most commonly used alkali sources are sodium hydroxide (SH) and sodium silicate (SS) [9]. Fibers are produced from steel, glass, and organic polymer (“synthetic”) fibers. Fiber-reinforced concrete possesses suitable characteristics, such as good formability, high strength, crack resistance, and improved flexural strength [10, 11]. Khamar and Kumar (2015) [12] found that the response of the hybrid fiber-reinforced geopolymer concrete was more balanced in terms of strength, and Guo et al. (2019) [13] found that hybrid fibers (HF) act to reduce stress concentration by preventing the formation of cracks in GPC. In this experimental study, the GPC consists of FA, Steel Slag (SG), and cement as raw materials to produce the geopolymer binder; also, the HF (steel and polyolefin) is added to the mixture in a specific ratio. The type of curing also affects the properties of hardened GPC, a compressive strength test was performed for the GPC specimens by Vijai et al. (2010) [14], who found that the compressive strength increases with age for the specimens in the ambient curing, but the heat or oven curing specimens had less increase in the compressive strength with age. There are studies that the GPC specimens were more stable and resistant to chemical attack than the normal concrete (NC) specimens when exposed to sulfuric acid and give better acid resistance than the NC [15], the reason for this is their aluminium-silicate oxide bridge (Al-Si-O) that is resistant to the acid attack and lower ratio of the calcium oxide lead to less formation of gypsum with no cracking and no changing in colour with little abrasion on the GPC specimens surface [16–18].

2.EXPERIMENTAL STUDY

2.1.Materials

In this paper, two types of cementitious materials (Low-calcium Class F FA and SG) according to ASTM C618 [19] and ASTM C989 [20], respectively, were used as partial-replacement materials for cement at a specific percentage (10%) to improve the binder process. Fly ash has been widely used in research when making geopolymer concrete as an alternative to OPC [21]. Tables 1-3 show the chemical and physical properties of the cement, FA and SG. Natural sand and crushed aggregate with maximum sizes of 4.75 mm and 12 mm were used as fine and coarse aggregates, respectively. The proportions of sand and gravel are 750 Kg/m^3 and 1040 Kg/m^3, respectively, for all mixes. Chemical Admixture (Superplasticizer): Aqueous Solution Modified Polycarboxylate High-Range Water-Reducing Admixture. Sika ViscoCrete®-5930 and Hyperplast PC200 were used to improve workability. Alkaline activator solution (AAS) was a mixture of SH (NaOH) obtained in flakes with purity, and molarity was 98% and 14 M, respectively, and the SS solution (Na_2O:13.7%, SiO_2: 33 and water: 53%) by mass. Two types of fibers, Hooked-end steel fiber (SF) & polyolefin fiber (POF), were used to improve the bonding characteristics and ductility of geopolymer composite [22, 23].

Table 1 Physical Properties of FA& SG.

Physical properties	FA	SG
Specific surface area (m^2/Kg)	420	550
Appearance / Color	Grey fine powder	Black Dark powder
Specific gravity	2.23	2.8

Table 2 Chemical Compositions of Ordinary Portland Cement.

Composition of OPC	By Weight %
CaO	62.3
MgO	3.42
SiO_2	21.87
Al_2O_3	6.29
Fe_2O_3	2.41
SO_3	2.37
Loss Of Ignition	0.94
Insoluble Residue	0.87
Free CaO	1.49
L.S.F.	86.2
C_3S	46.7
C_2S	27
C_3A	10
C_4AF	7.33

Table 3 Chemical Compositions of FA& SG.

Chemical properties (%)	FA	SG
CaO	3.11	23.53
MgO	2.65	1.49
SiO_2	49.67	45.52
Al_2O_3	19.73	10.61
Fe_2O_3	18.42	15.8
SO3	0.34	0.092
MnO_2	--	0.08
TiO_2	--	0.14
K_2O	--	0.99
Na_2O	--	0.23
P_2O_5	--	0.06
Loss Of Ignition	3.71	1.21
C_3A	42.38	--

2.2. Mix Design, Casting and Curing Process

The experimental work in this paper is to produce Fiber Reinforced GPC and study the mechanical performance of specimens under two curing conditions. There were 20 mixes cast in this work, with two different proportions of extra water. Several trial mixes were cast, and the best mix was chosen. The total binder content of 375 kg/m^3 contains (70% fly ash, 20% slag and 10% cement) by weight. SF was used by a ratio (0%, 0.5%, 1% and 1.5% by volume of the concrete and hybrid SF 0.5% and PF 0.5%; these proportions were added to the ingredients before the AS. The AS was prepared at least 24 hrs prior to assessing the solution's reactivity [24]. The AA/Binder=0.5 and SS/SH=1.5 were for all mixes, and 14 molarity of NaOH was used for all mixes; the higher the concentration or molarity of NaOH, the higher the compressive strength of concrete [25]. For the mixing process, the fine and coarse aggregates with CMs were blended for 2 min in the mixer [2]. Then the fibers were added to the ingredients. Next, the extra water, AA and superplasticizer were added to the mixture together and mixed for 4 min [26], to achieve a uniform mixing. If fiber is present, it is added before mixing the AAS with the dry ingredients to ensure the fibers are distributed, and no clumping occurs [27]. The standard moulds, Cubes (100*100*100) mm, Cylinders (100*200) mm, and Beams (100*100*400) mm, were prepared to evaluate the mechanical performance of specimens as shown in Fig. 1. After that, fresh concrete is ready for slump testing and distributed in the moulds. The curing method is done after 24 hrs. of the casting process. After demolding, the specimens were cured in the oven at 65°C for 24 hrs [28]; after 24 hrs, the specimens were kept at room temperature until the day of the test [29]. The other specimens were cured at ambient temperature. The higher the molarity or concentration of NaOH in the GPC specimens, the higher the compressive strength when heat curing is used [30]. Fig. 1 shows the details of mould preparation and GPC specimens during the curing period.

(a) (b)

Fig. 1 (a) The Moluds Preparation and (b) GPC Specimens During the Curing Period.

Table 4 Mixture Proportion of GPC.

Mix	Binder kg/m³			NaOH kg/m³	Na_2SiO_3 Kg/m³	%SF	POF %	Extra water %	Curing
	Cement	Fly ash	Slag						
MA1	37.5	262.5	75	75	112.5	0	-	11	Ambient
MA2	37.5	262.5	75	75	112.5	0.5	-	11	Ambient
MA3	37.5	262.5	75	75	112.5	1	-	11	Ambient
MA4	37.5	262.5	75	75	112.5	1.5	-	11	Ambient
MA5	37.5	262.5	75	75	112.5	0.5	0.5	11	Ambient
MA6	37.5	262.5	75	75	112.5	0	-	9	Ambient
MA7	37.5	262.5	75	75	112.5	0.5	-	9	Ambient
MA8	37.5	262.5	75	75	112.5	1	-	9	Ambient
MA9	37.5	262.5	75	75	112.5	1.5	-	9	Ambient
MA10	37.5	262.5	75	75	112.5	0.5	0.5	9	Ambient
MO1	37.5	262.5	75	75	112.5	0	-	11	Oven
MO2	37.5	262.5	75	75	112.5	0.5	-	11	Oven
MO3	37.5	262.5	75	75	112.5	1	-	11	Oven
MO4	37.5	262.5	75	75	112.5	1.5	-	11	Oven
MO5	37.5	262.5	75	75	112.5	0.5	0.5	11	Oven
MO6	37.5	262.5	75	75	112.5	0	-	9	Oven
MO7	37.5	262.5	75	75	112.5	0.5	-	9	Oven
MO8	37.5	262.5	75	75	112.5	1	-	9	Oven
MO9	37.5	262.5	75	75	112.5	1.5	-	9	Oven
MO10	37.5	262.5	75	75	112.5	0.5	0.5	9	Oven

3.RESULTS AND DISCUSSION

3.1.Workability of Fresh GPC

The concrete slump test was measured using a metal slump cone after mixing the components in accordance with ASTM C143/C143-15a [31]. Workability is an important property used to determine the suitability of concrete for casting. The fibers may adversely affect the workability of fresh GPC; this problem could be addressed by increasing the SP dosage and adding additional water. The surface area of the fibers often absorbs more binder, increasing the viscosity of fresh concrete and resulting in low slump values [32]. The addition of fibers reduced the slump; when using 11% of the extra water with the first type of superplasticizer (Sika ViscoCrete®-5930), the slump was obtained 89 mm (0% SF), 85 mm (0.5%SF), 80 mm (1%SF), 76 mm (1.5%SF) and 79 mm (1% HF). As for when using 9% of extra water with the second type of superplasticizer (Hyperplast PC200), the slump was obtained 93 mm (0% SF), 90 mm (0.5% SF), 85 mm (1% SF), 81 mm (1.5% SF) and 88 mm (1% HF). To maintain workability, extra water has been added by 11% and 9% of the binder content. Fig. 2 shows the influence of fibers on the slump. The researchers found that the particle shape of CMs also negatively influences workability, whereas slag particles have sharp edges, which may decrease the workability of the GPC [33]. While FA has a spherical shape, which can improve the workability of fresh GPC [34].

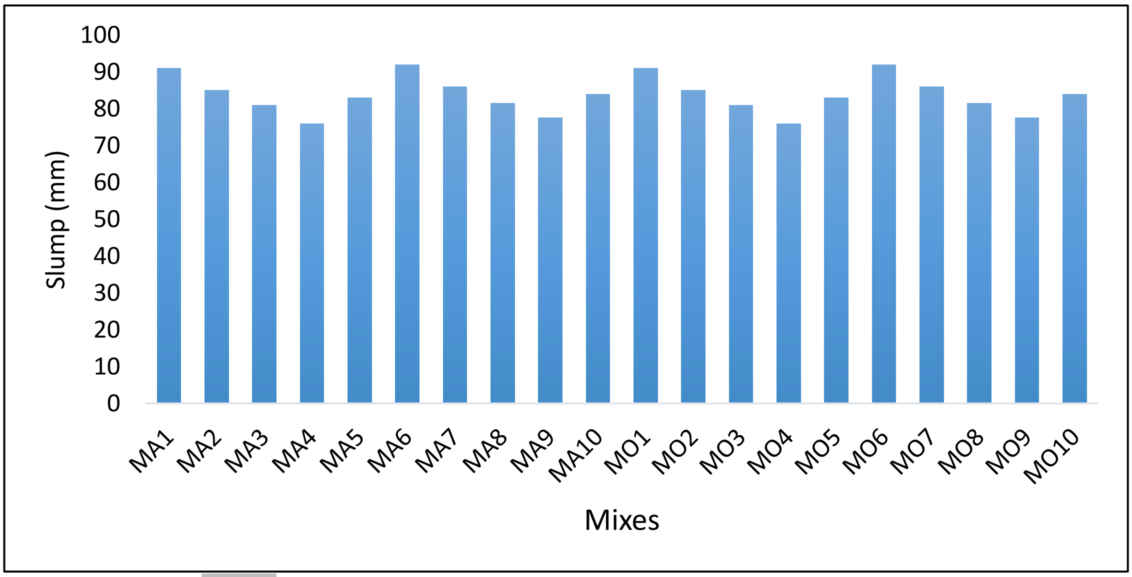


Fig. 2 Effect of the Addition of SF and HF on the Workability.

3.2.Compressive Strength

The compressive strength test was conducted in accordance with BS 1881, part 116, at ages 7, 28 and 56 days. The cube specimens used for this test were (100×100×100) mm. The compressive strength was calculated from the average of three specimens for each mix. Fig. 3 illustrates the effect of fibers on the compressive strength at ambient curing conditions, and Fig. 4 at oven curing conditions, respectively. Based on the GPC test results, the compressive strength at early ages in oven curing was higher than in ambient curing, due to the high temperature accelerating the reaction of AS in the specimens within 24 hours. As for the later ages, the increase in the results of the ambient curing was higher than the increase in the results of the oven curing due to the presence of CaO compound in the CMs in a lower percentage than in the cement, because it retards the reaction process, based on the XRF test of CMs and previous studies [35, 36]. The highest compressive strength (without fibers) was 31.5 MPa for GPC specimens. The SF improved the compressive strength; the highest strength value, at a 1.5% SF content, was 48 MPa. Mix (1% SF) was selected and studied with HF. The results obtained for the HF specimens were between (0.5% SF) and (1% SF) mixes. The increases in compressive strength at 0.5%, 1%, and 1.5% SF at later ages were 20%, 33%, and 49%, respectively. As for the HF mixture, the increase in compressive strength was 24%. The curing period mentioned by Hardjito et al. (2004) [5] states that increasing the curing period improves compressive strength, which increases gradually over time, and that calcium dissolution from CMs influences compressive properties [37]. Lower CaO content also makes GPC less susceptible and more stable to chemical attacks than OPC concrete [15]. Lower strength was observed when using 11% extra water; to address this issue, the type of chemical admixture was replaced by another and the extra water was reduced to 9%. There is also a strong linear relationship between slump values and compressive strength (R2=0.96) in Fig. 5.

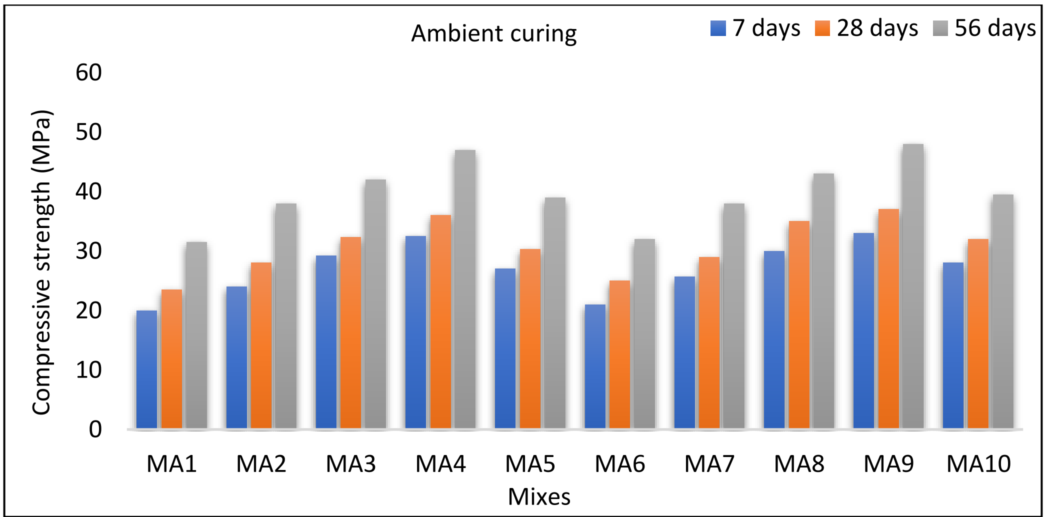


Fig. 3 Compressive Strength Test Results at Ambient Curing Conditions.

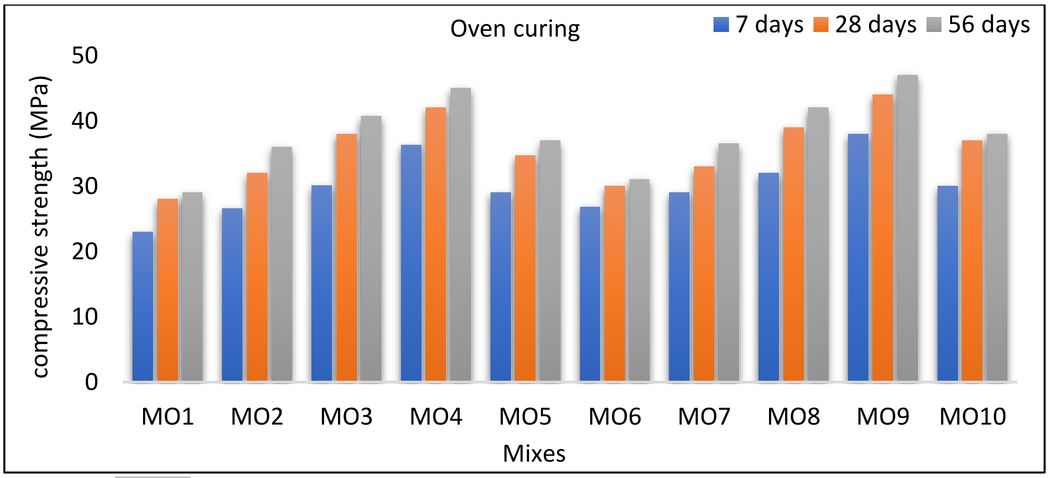


Fig. 4 Compressive Strength Test Results at Oven Curing Conditions.

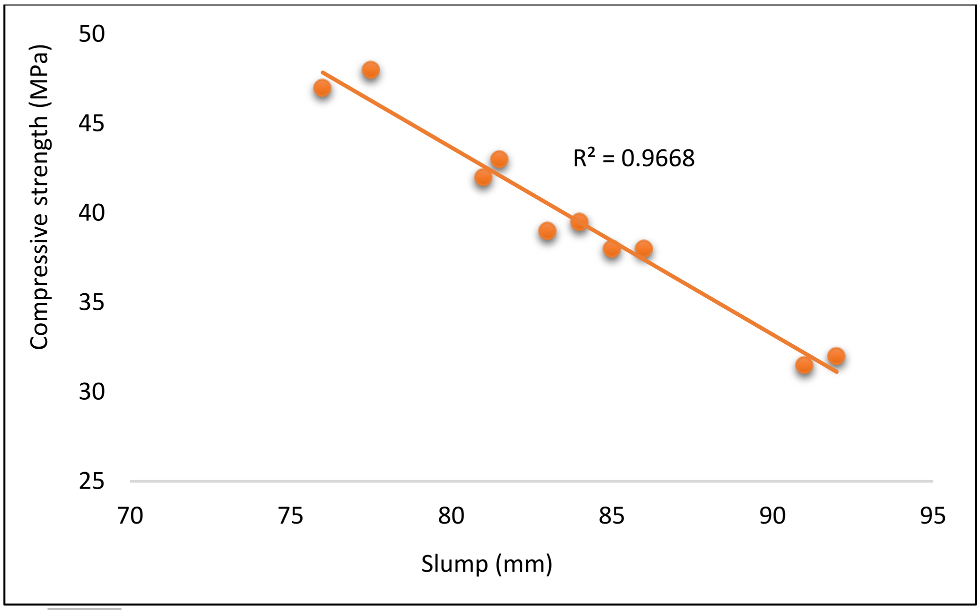


Fig. 5 Relationship between the Compressive Strength for GPC and Slump.

3.3.Flexural Strength

The flexural strength test was conducted in accordance with ASTM C78-15a [38]. The prism specimen was used with dimensions (100 × 100 × 400) mm to determine the flexural strength under four-point bending loading and was loaded at a rate of 0.03 mm/min under displacement control. The test was conducted at 7, 28 and 56 days. The effect of steel fibers was evident on flexural strength for specimens, which enhances not failure or fracture of the specimen with the appearance of a crack at the bottom of the load, which improves the post-crack behaviour of specimens with reducing of its width [39, 40] and this is attributed to the more bond between GPC composites and SF [41]. The results were obtained and shown in Figs 6 and 7 in the two curing conditions. The highest flexural strength was 7.1 MPa (1.5% SF) for MA9 at ambient curing and 6.9 MPa (1.5% SF) at oven curing. The reason for the increase in flexural strength, except for the existing fibers, is also owed to the high percentage of the CMs in GPC composition [42]. Adding HF improves flexural strength to a certain extent; the higher the fiber content, the higher the flexural strength; this is done by preventing cracks from growing [13]. The flexural strength performance for HF mixes was obtained as 5.7 MPa for MA10 at ambient curing and 5.6 MPa for MO10 at oven curing.

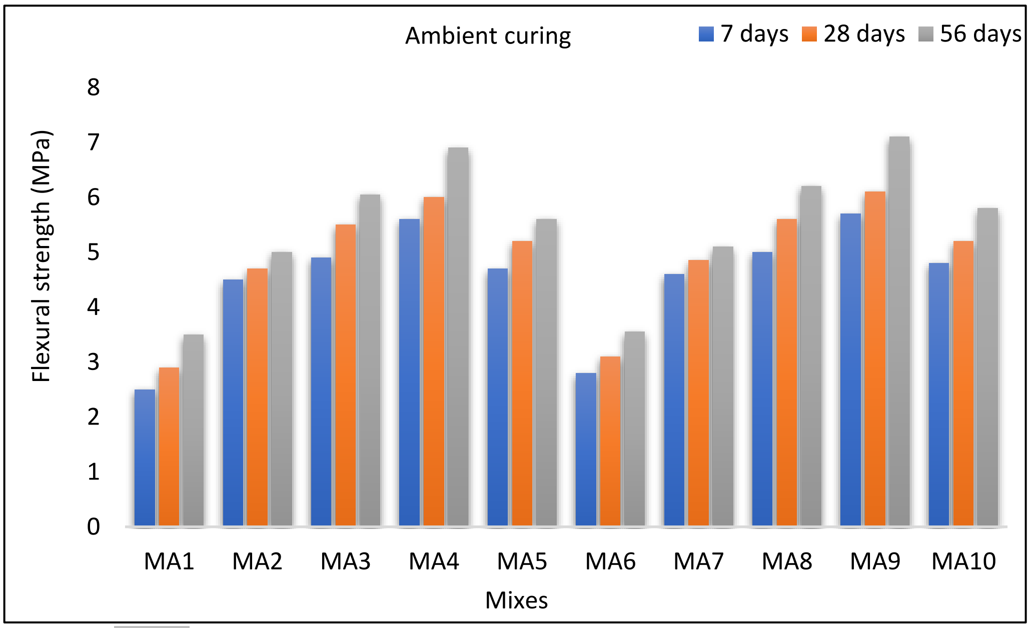


Fig. 6 Flexural Strength Test Results at Ambient Curing Conditions.

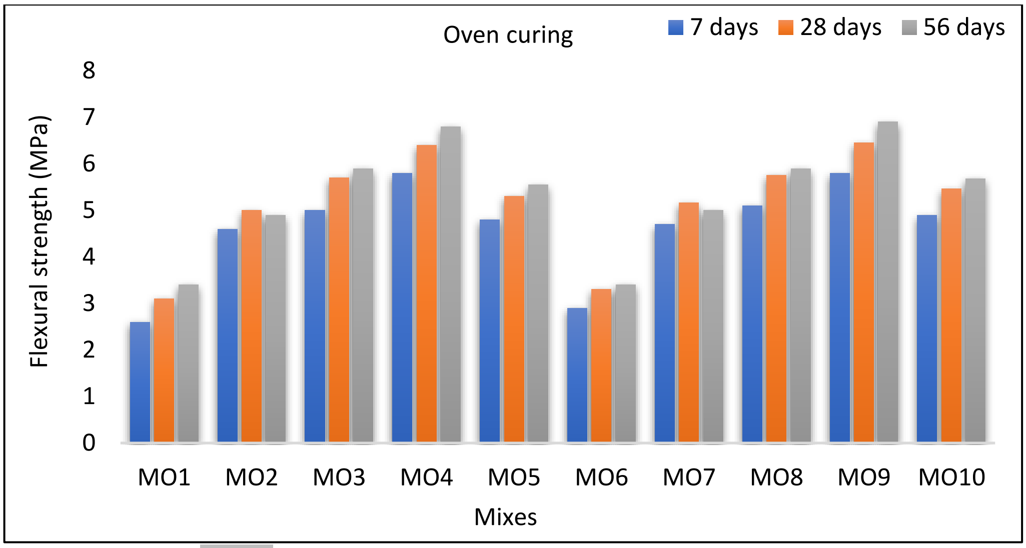


Fig. 7 Flexural Strength Test Results at Oven Curing Condition.

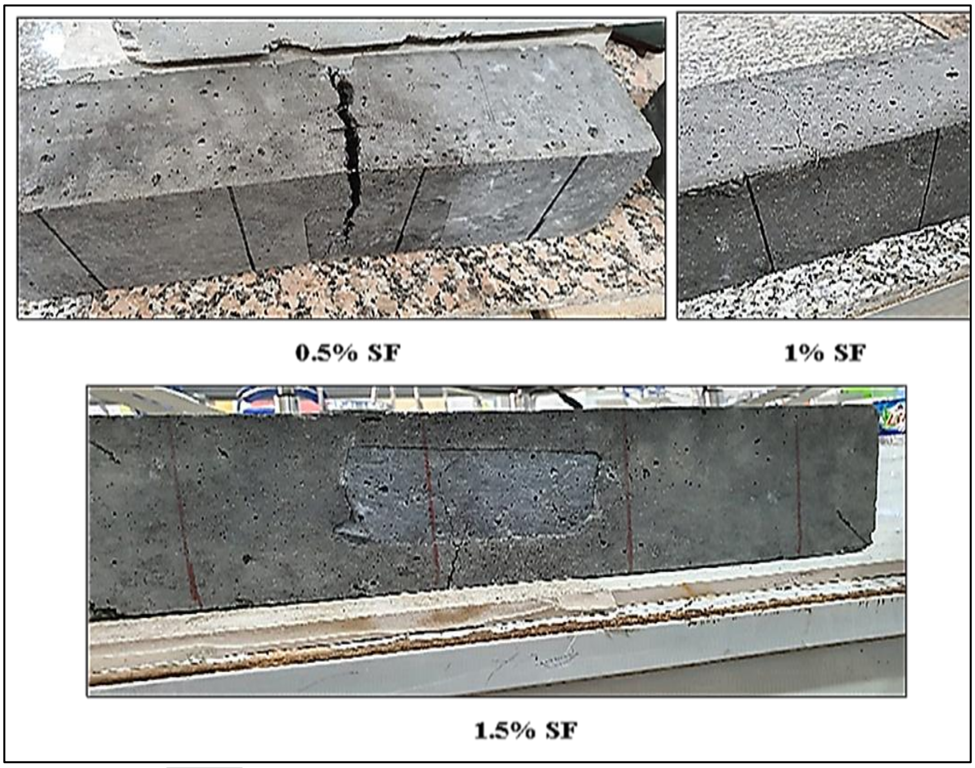


Fig. 8 Patterns of Failure of Beams Containing Fibers.

3.4.Splitting Tensile Strength

The cylinder specimens (100 mm diameter and 200 mm high) in accordance with ASTM C496/C496 [43], were used for testing at ages 7, 28 and 56 days. Figures 9 & 10 illustrate the splitting tensile strength test results. The results indicated that splitting tensile strength increased with fiber content; this has been confirmed in previous studies. The SF has a high bond strength to the GPC [44], and GPC specimens exposed to 65 ℃ yielded higher results at an early age. The splitting tensile strength was higher at 4.6 MPa for MA9 and 4.5 MPa for MO9 than in mixes without fibers. The conclusion is that the SF is directly related to the splitting tensile strength of GPC components [45], which reduces cracking in GPC specimens; thus, brittle failure is reduced, and ductile failure occurs [46–48]. In general, the specimen without steel fibers produces a fracture in the middle, while the specimens containing the steel fibers produce cracks in the center (Fig. 12) shows failure mode of the cylinder specimens. In addition to the steel fibers, studies indicate that the mixture's components affect the tensile strength. Deb et al. (2014) [49] indicated that splitting tensile strength increased with increasing slag content up to 20% in the FA-GPC. A high relationship between flexural strength and splitting tensile strength was observed (R2: 0.99) for all specimens, as shown in Fig. 11.

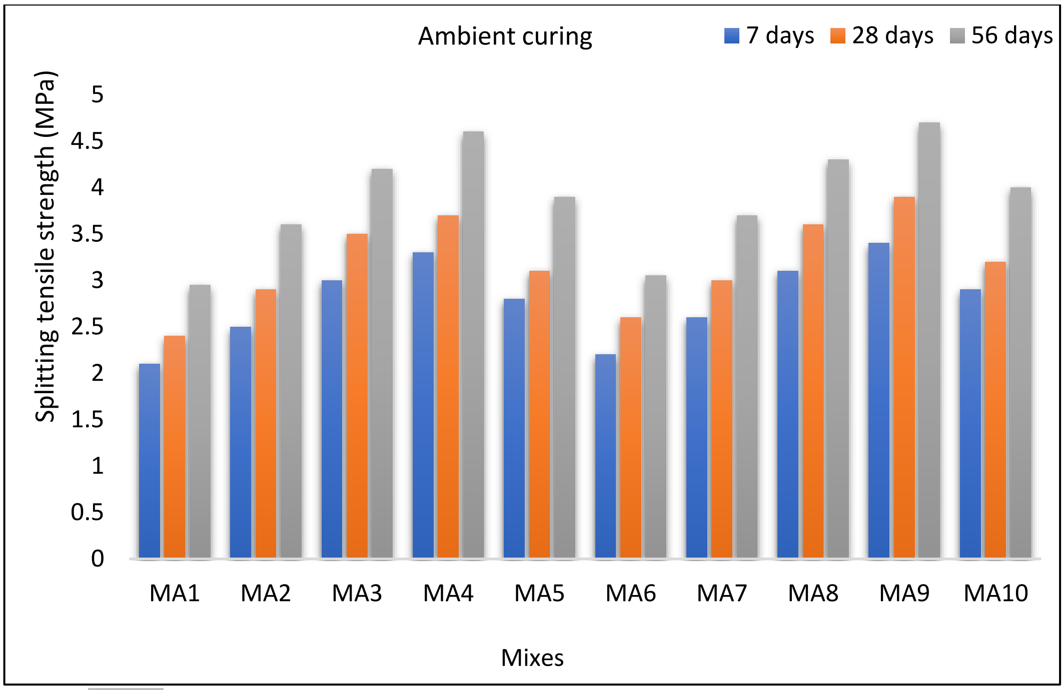


Fig. 9 Splitting Tensile Strength Test Results at Ambient Curing Condition.

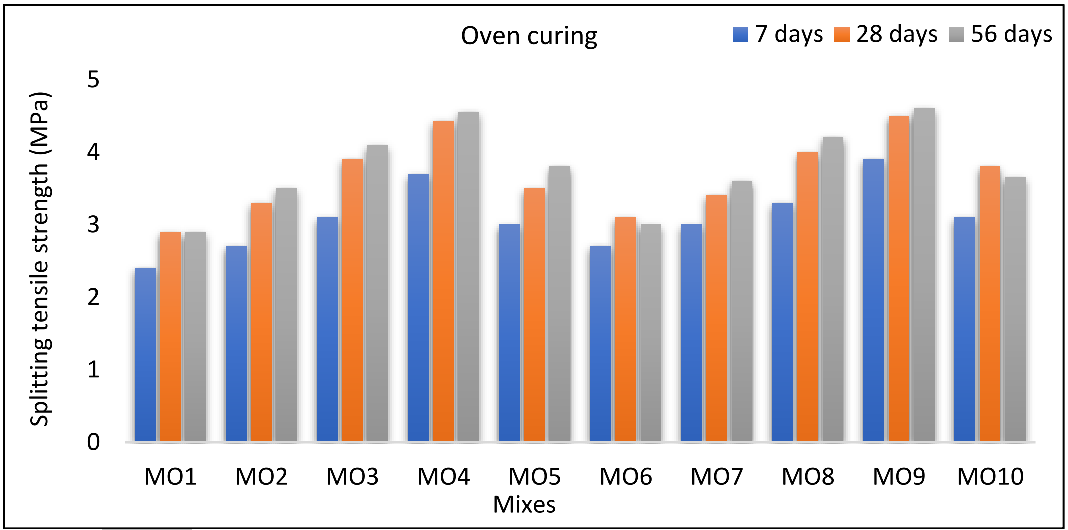


Fig. 10 Splitting Tensile Strength Test Results at Oven Curing Condition.

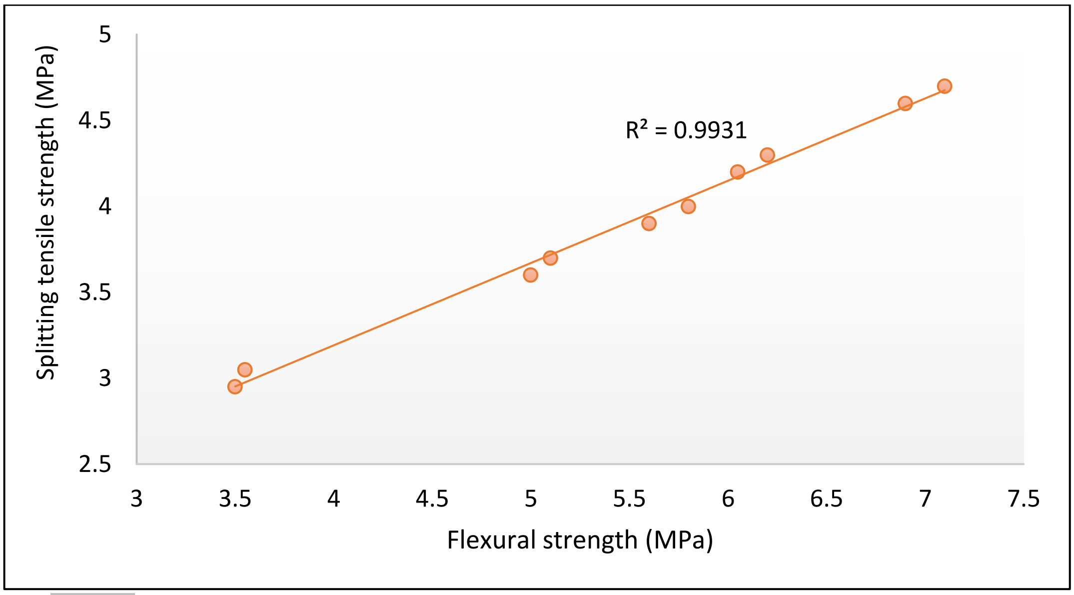


Fig. 11 The Relationship between Flexural Strength and Splitting Tensile Strength.

GPC 1% **GPC 1.5%**

Fig. 12 Failure Mode of the Splitting Tensile Strength Specimens.

3.5.Modulus of Elasticity

The modulus of elasticity measures a material's resistance to elastic deformation under applied force. Fig. 13 shows the modulus of elasticity results for all the mixes at 28 days. Cylinder specimens (100*200 mm) were tested at 56 days in accordance with ASTM C469-96 [50]. As we know, there is a direct correlation between the increase in elasticity modulus and its compressive strength for normal concrete [51]. According to previous studies, some studies showed that the modulus of elasticity of GPC is lower than the modulus of elasticity of NC and about 10% lower than OPC, both have the same compressive strength [52], and also 11–16% modulus of elasticity for FAGPC is less than the theoretical value predicted using ACI 318. Puertas et al. (2003) [53] observed that, by conducting a comparison of the mortar between a pulverized fuel ash (PFA) and an AA and an OPC mortar, the PFA mortar had a lower modulus of elasticity than the OPC mortar. To improve the mechanical properties of GPC, the fibers can be used. The researchers preferred steel fibers due to their high modulus of elasticity and fracture strain [54, 55]. As seen in Fig. 13, the addition of SF in GPC mixes does not affect the apparent modulus of elasticity values. Many researchers reported that including SF in GPC has little effect on the modulus of elasticity value [56–58]. The highest result of modulus of elasticity of GPC is of SF 1.5% ratio of 28.5 GPa with ambient curing and 31 GPa with oven curing. The correlation between the modulus of elasticity and the compressive strength of the GPC cylinder has been plotted in Fig. 14. There is a linear trend between compressive strength and modulus of elasticity.

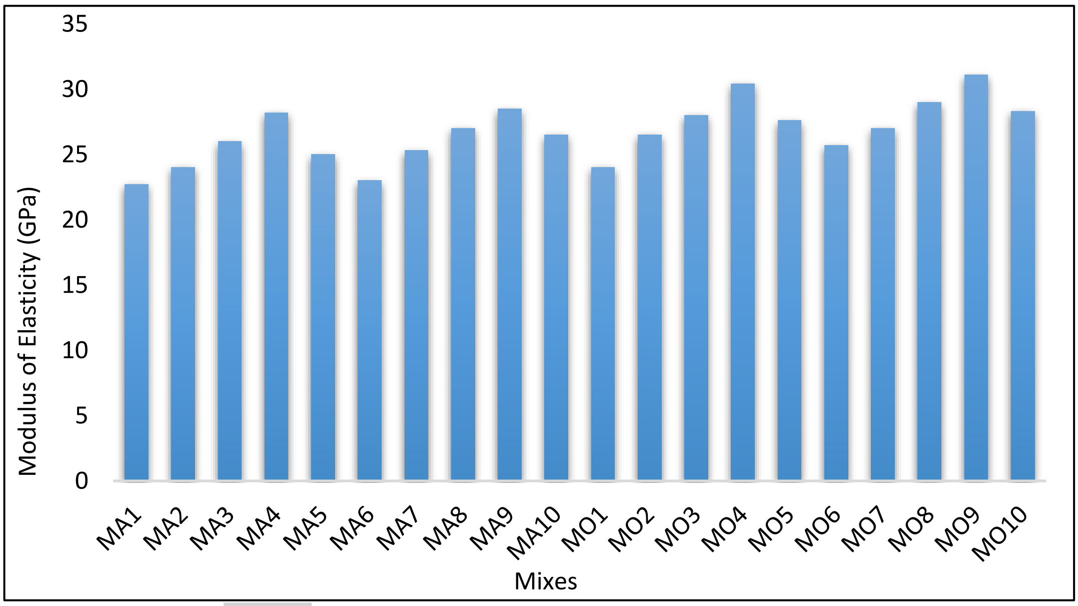
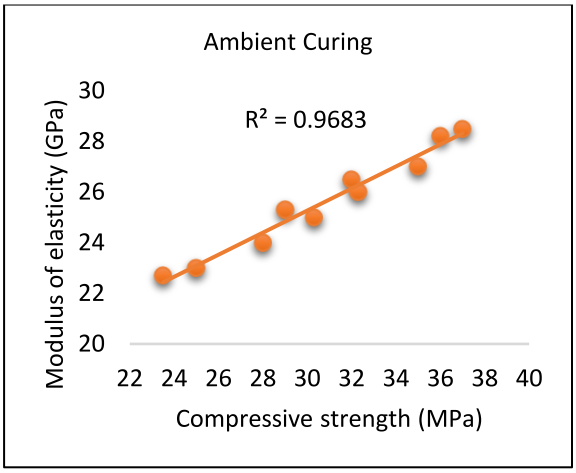


Fig. 13 Modulus of Elasticity Test Results at 28 Days.



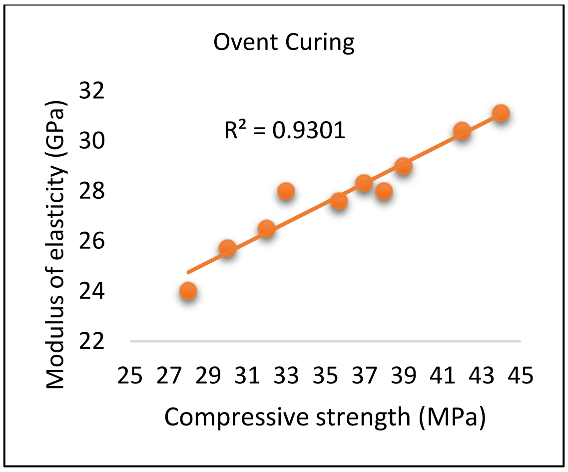


Fig. 14 The Linear Relationship between Compressive Strength and Modulus of Elasticity at 28 Days.

4.CONCLUSIONS

The effect of different curing conditions and fibers on the mechanical performance of GPC was studied. As a result, the following conclusions were drawn:

1) GPC is less harmful to the environment and more sustainable because it can replace traditional Portland cement concrete with CMs across a variety of applications, such as precast units.
2) Adding SF and HF reduces the slump properties of fresh concrete, so an increase in extra water to 11% or 9% of the binder ratio, with a SP dosage of 1.5% in the fresh concrete, is needed to improve workability.
3) Adding SF 0.5%, 1% and 1.5% significantly increases compressive strength. It increases compressive strength by about 20%, 33%, and 49% at 56 days, respectively, and flexural strength by 43%, 74%, and 99%, respectively.
4) The incorporation of 0.5% of SF with 0.5% of POF provides an improvement in compressive strength and flexural strength of about 20% and 63% for GPC, respectively, at 56 days.
5) The splitting tensile strength of GPC increased with fiber content at 0.5%, 1%, and 1.5%. It increased the splitting tensile strength by about 21%, 41% and 54%, respectively. As for HF, the increase in GPC was about 31% at 56 days.
6) The addition of SF to GPC mixes had little effect on the modulus of elasticity. The increase in modulus of elasticity for GPC with 0.5%, 1%, and 1.5% fiber content was about 8%, 16% and 25%, respectively, with heat curing and about 5%, 12%, and 20%, respectively, with ambient curing. And HF was about 10% for GPC.
7) Considering compressive, flexural, and splitting strength, the 1% of fiber content was considered the best in terms of mechanical strength and workability.
8) The use of Hyperplast PC200 with 9% reduced the amount of extra water; thus, the compressive, fracture, and splitting tensile strengths increased more than those of Sika ViscoCrete®-5930.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Alaa Y. Hussein, Hammad M. Abd: Writing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. *Hasan M. Ahmed Albegmprli:* Review, editing, Supervision, Project administration.

DECLARATION OF COMPETING INTEREST

We declare that we have no known competing financial interests or personal relationships that could have appeared to influence the work presented in this paper.

ACKNOWLEDGEMENTS

The authors extend sincere thanks and profound appreciation to the Building and Construction Engineering Techniques / Technical Engineering College of Mosul – Northern Technical University, for the scientific and financial support provided through the Postgraduate Research Grant, the second open session of the Mosul Technical Engineering College of Mosul Council / Northern Technical University / No. (S/18/4169 on 11/16/2021), which played a vital role in the successful completion of this study. Special appreciation is also given to the laboratories of the College of Technical Engineering, College of Mosul, for their advanced facilities and technical capabilities, which significantly contributed to the experimental work and the achievement of the research objectives. The authors further express deep gratitude to the Northern Technical University for hosting this research project and for fostering an academic environment conducive to its implementation.

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