Mechanical properties of geopolymer concrete reinforced with steel fibers under ambient and elevated temperatures

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Abstract*— The objective of the current study to study and improve the compressive strength and tensile strength of geopolymer concrete (GPC). Ground granulate blast furnace slag (GGBFS), fly ash (FA) , and ordinary Portland cement (OPC) are used as a binder materials to develop the GPC mixes. The alkaline solution was a mixture of sodium silicate and sodium hydroxide. The binder material ratio was utilized to manufacture GPC 50% GGBFS, 40%FA, and 10% OPC. The total binder weight was 420 Kg/m3, within a constant alkali-binder proportion (0.4%), and with three volumetric ratios of steel fiber (SF). The specimens were cured at ambient temperature. The compressive strength and splitting tensile strength of GPC are evaluated at age 28 days, before and after three levels of fire exposure. The results showed that the mechanical properties enhanced by increasing the replacement ratio of SF from 0%to 1%, show an increasing in the compressive strength and tensile strength by (59% and 150%) respectively. No degradation in the residual mechanical properties was observed when exposed to fire at temperature up to 750°c.*Index

Key words: Geopolymer concrete, binder materials, fly ash , ground granulate blast furnace slag, compressive strength and tensile strength.

INTRODUCTION

Concrete is the most commonly utilised construction material because its being available of raw ingredients and simple of use. The cement industry's usage of fossil fuels and decarbonisation of limestone leads to large CO_2 emissions. In addition to aluminium and steel, ordinary Portland cement (OPC) is among the most high in energy materials [1,2]. As result of the bad environment impact of carbon dioxide, as well as the high energy demand, are key worries for cement manufacturing and civilization's future. To solve environmental concerns, new ecologically friendly structural materials are being used as an alternative to traditional concrete [3,4,35]. Geopolymer has emerged as a sustainable alternative to standard OPC concrete [5, 6]. The large reduction in CO_2 emissions, as in addition the rising need for resources of nature, has sparked interest in geopolymer concrete. Unlike OPC, raw material production does not involve calcination, thus energy. consumption is reduced. Geopolymer concrete (GPC) emits five to six times lesser CO_2 than OPC concrete [7,8]. GPC decreases carbon dioxide emissions and utilises by-product waste from aluminosilicate synthesis to create new construction materials [9]. A geopolymer is produced when aluminosilicate compounds are mixed with natural substances like clay and metakaolin or with industrial materials, Such as examples fly ash and powdered granulated blast furnace slag [10,11]. In general, GPC is made up of activators and variety Aluminosilicate sources, with or without OPC [12]. Several research studies have explored the use of fly ash (FA) and ground granulated blast furnace slag (GGBFS) as SCMs because they increased the mechanical performance of concrete, were affordable, and environmentally environmentally friendly concrete [13,14,34]. The second essential GPC component required to free up the silica and alumina contents of aluminosilicate are alkaline activators. Sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) are the two alkaline activators that are majority frequently employed [15]. They are used in concrete to minimize costs while also enhancing workability and hardened state qualities, and they are more environmentally friendly materials [16,17]. Fibers can be used to enhance the mechanical performance of geopolymer concrete, just like traditional concrete . The tensile and flexural strength of geopolymer concretes were significantly improved by steel fiber among other fibers[18,19].

High temperatures affect the mechanical and physical qualities of concrete. An increase in the temperatures caused by fire might lead to permanent deterioration in the strength of concrete and a reduction in its cross-sectional area due to spalling of the concrete cover. Geopolymer concrete has good thermal characteristics, and no spalling has been seen after fire exposure [20].Previous studies have demonstrated that GPC specimens had a higher compressive strength than OPC specimens under ambient and heat curing conditions [21,22,23].

Still , there are very little research in the literature on the mechanically and fresh properties of FA/GGBFS-based GC. More research is needed to develop GC's fresh and mechanical qualities. Due to its recentness, there are little research studies on the impact of high temperatures on geopolymer concrete properties .As a result, the purpose of this study is to examine how steel fiber (SF) affects the mechanical characteristics of GPC, including as its compressive, tensile, and to examine the effects of 250°C, 500°C, and 750°C fire exposure on the mechanical characteristics of GPC.

ii. Materials

FA, ASTM C618-based Type-F [24], GGBFS, and cement used as materials for binder. The total binder amount was 420kg/m3 and a constant ratio of alkali activator/binder (0.4)

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were proportioned. The appropriate concentration of 14M for sodium hydroxide solution. The binder ratios were utilized to produce GPC (40%FA,50%GGBFS, and 10% OPC). The cement is manufactured in Iraq based on Iraqi Specification No. 5/1984.The properties of OPC are shown in Table (1). FA and GGBFS were acquired from a local vendor in Iraq's Erbil. Table(2) illustrate the properties of FA and GGBFS. Both fine and coarse aggregate were created using local sand from the Qara Salem region close to Kirkuk City, Iraq. The properties of the aggregates according to IQS 45/1984 are shown in Tables (3) and (4).

Alkali activators include solutions of sodium silicate (Na2SiO3) and sodium hydroxide (NaOH). The properties of NaOH and Na2SiO3 are shown in Tables(5) and (6) respectively. The Na2SiO3 (Na2O: 13.7%, SiO2: 33%, and water: 53.3% by mass) was supplied by a local provider in Erbil, Iraq [25]. The best Na2SiO3/NaOH ratio for economic reasons was found to be 1.5-2.5, as previous tested [26]. A third-generation polycarboxylate has a density of 1.096 g/cm3 was used as a superplasticizer to obtain good flowability while avoiding segregation and/or bleeding [27]. The steel fiber used in this research are hooked- ends. The properties of steel fiber are shown in Table (7).

TABLE (1) PROPERTIES OF CEMENT

Compound composition	Chemical composition	Percentage by weight	Limits of Iraqi specification No. 0.5/1984
Lime	CaO	61.18	-
Silica	SiO_2	21.46	-
Alumina	Al_2O_3	4.52	-
Iron Oxide	Fe_2O_3	3.71	-
Magnesia	MgO	2.29	<5.0
Sulfate	SO_3	2.75	<2.80
Loss of ignition	L.O.I	2.43	<4.0
Insoluble residue	I.R.	0.92	<1.5
Lime saturation factor	L.S.F.	0.90	(0.66-1.02)%
Tricalcium silicate	C_3S	42.84	-
Dicalcium silicate	C_2S	29.32	-
Tricalcium Aluminate	C_3A	5.78	>5.0
Tricalcium Alumino ferrite	C_4AF	11.2	-

Table(2) Properties of FA and GGBFS

Composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	LOI
GGBFS(%)	46.87	24.23	0.32	36.0	5.05	0.05	0.00	5.0	2.4
FA(%)	66.65	25.06	1.68	2.03	0.1	1.01	0.39	0.62	3.57

Table(3) Properties of fine aggregate

Sieve size (mm)	Fine aggregate passing by weight (%)	(IQS 45/1984) limitations for zone2.
10	100	100
4.75	95.6	90-100
2.36	79.5	75-100
1.18	64.7	55-90
0.6	50.3	35-59
0.3	15.5	8-30
0.15	3.2	0-10

Table(4) Properties of coarse aggregate

Sieve size (mm)	Coarse aggregate passing by weight (%)	(IQS 45/1984) limitations for zone2.
20	100	100
14	100	90-100
10	60.5	50-85
5	0.8	0-10

Table(5) Properties of NaOH

Appearance	Unit Measuring	ASTM E291	Results
Sodium hydroxide (NaOH)	%	97.5 (min)	98.4
Sodium carbonate (Na_2CO_3)	%	0.40 (max)	0.36
Sodium chloride (NaCl)	%	0.15 (max)	0.08
Iron oxides (Fe_2O_3)	%	0.01 (max)	0.004
Sulfate as Na_2SO_4	ppm	200 (max)	73
Copper as Cu+2	ppm	4.0 (max)	0.1
Nickel as Ni+2	ppm	5.0 (max)	2.35
Manganese as Mn	ppm	4.0 (max)	0.022
Silicate as SiO_2	ppm	2 (max)	13.3
Water Insoluble	ppm	200 (max)	62

Table (6) Properties of Na2SiO3(*)

Descriptions	Value
Ratio SiO_2 / Na_2O	2.4 ± 0.05
Na_2O % by weight	13.10 – 13.70
SiO_2 % by weight	32.00 – 33.00
Density - 20° Baumé	51 ± 0.5
Specific Gravity	1.534 – 1.551
Viscosity (CPS) 20°C	600 – 1200
Appearance	Hazy

(*) Data from datasheet

Table(7) Properties of steel fiber

Descriptions	Hooked end
Length(mm)	35 mm
Diameter(mm)	0.55mm
Density(Kg/m^3)	7850 Kg/m^3
Tensile Strength(MPa)	1345 MPa
Aspect Ratio(L/D)	64

III. Mixture Design, Mixing Method and Curing Regime

FA , GGBFS and OPC are employed in the development of GC mixes as binder components. The total binder amount was 420 Kg/m3. The Alkaline Activator to Binder ratio (AA/B) is fixed at 0.4, and the ratio of Na2SiO3/NaOH is 2.5. The binder ratio were used to production GPC (10%OPC, 40FA and 50%GGBFS).The mix proportions used in this study were

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showed in Table (8). In this work, several SF volume fractions are created of (0, 0.5, 0.75, 1)% of the volume of geopolymer concrete, as display in Table(9). The optimum mixing technique for GPC mix design, as demonstrated in Figure(1).The mixing procedure is displayed in Figure(2), which was adopted by Gomaa et al. (2018) [28]. The cubes (100*100*100) mm, were conducted under compression load according to (BS-EN-12390-3, 2009) [29] requirements, and cylinders (100*200) mm based on (ASTM-C496-17, 2017)[30] were prepared to investigate the mechanical performance of specimens. At each temperature level, four preparations are made. Each batch contained 12 cubes, and 12 cylinders totaling 36 specimens. All samples were demould after 24-48 hrs depending on the hardening state and left in the laboratory room under ambient temperature (21±2)°CC until the test day (28d). Then the residual compressive strength and splitting tensile strength is performed on the specimens exposed to varying intensity of fire (250˚c,500˚c, and 750˚c) . The fire is exposed for two hours (ASTM-E119, 2020)[31]. To crush the samples using a hydraulic machine of 2000 KN, capacity (Figure 3),with an average of three cubes for each GPC mix.

Table(8) Mix proportions of GPC

Constituent	Binder(Kg/m^3)			C.Agg. (Kg/m^3)	F.Agg (Kg/m^3)	NaOH (kg/m^3)	Na_2Sio_3 (kg/m^3)	SP (%)	Extra water (%)
	Cement (10%)	FA (40%)	GGBFS (50%)						
Amount	42	168	210	1250	690	20.8	129	3	10

Table (9) Fibers content

Mix designation	Steel Fiber (Vf%)
G1-0%SF	reference
G2-0.5%SF	0.5
G3-0.75%SF	0.75
G4-1%SF	1

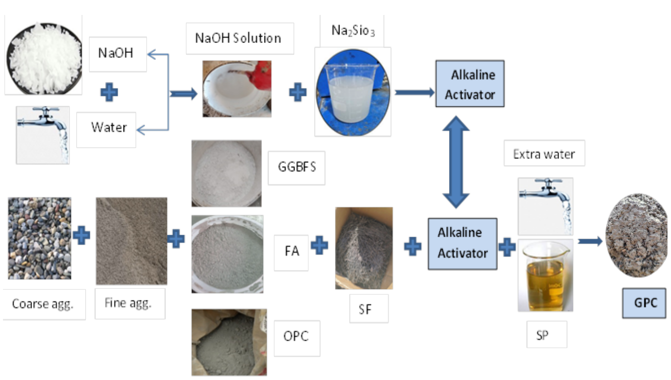

Figure (1) Mixing scheme of GPC

Step 1/ Mixing coarse and fine aggregate for 1 minutes

Step 2/ Adding the GGBFS, FA , and Cement with continuing mixing for 2 minutes

Step 3/ Adding the SF with continuing mixing for 2 minutes

Step 4/ Adding the alkaline solution with continuing mixing for

Step 5/ All components were mixed for additional 3 minutes (with SP) or until a homogeneous mixture to be obtained

Figure (2) Flow chart of mixing steps procedure of GPC

Figure (3) a/ cubic compressive strength, b/cylinder tensile strength, c/ mixture Out put

IV.EXPERIMENTAL RESULTS

A.1 Compressive strength of GPC

A.1.1 Effect of Steel Fiber at Ambient Temperature

Figure (4) display results of the cube compressive strength test for each mix. Steel fiber-incorporated geopolymer concrete specimens had a greater cubic compressive strength than regular geopolymer concrete [32]. The increase in compressive strength for mixes(G2-0.5%SF ,G3-0.75%SF and G4-1.0%SF) at 0.5%, 0.75% and 1.0% of SF was 21%, 35% and 59%, respectively. The compressive strength was enhanced by the SF; the highest strength value at 1.0% of SF content was 51.2 MPa. The lowest cubic compressive strength in specimen G2-0.5%SF which contain 0.5% steel fiber is 38.8 MPa, this is remain higher than in geopolymers concrete without steel fibers. Figure (5) shows the damage caused of GPC specimens followed the cubic compressive testing.

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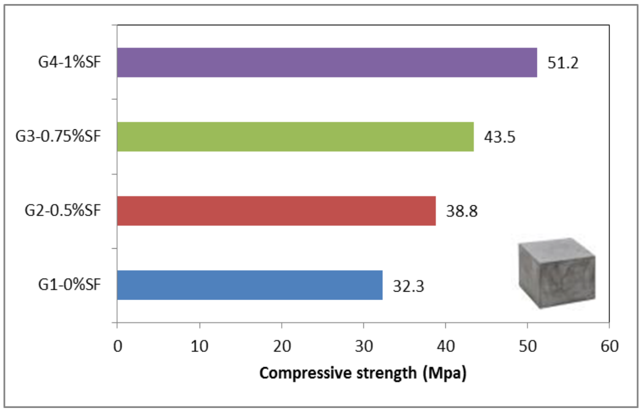


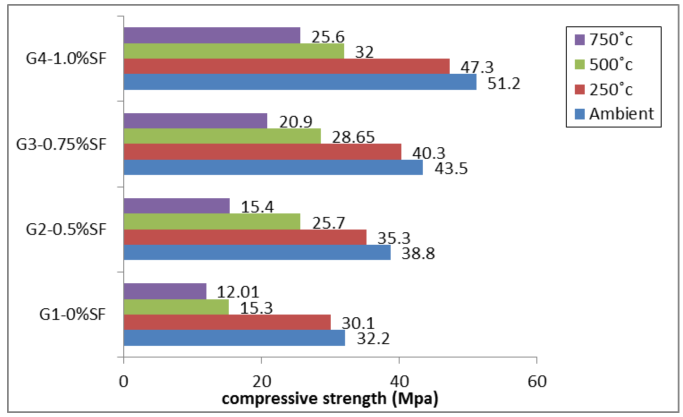
Figure(4) Results of compressive strength at ambient temperature

Figure(5) Specimen damage patterns after the cubic compressive strength test

A.1.2 Effect of Steel Fiber at Elevated Temperature After Fire Exposure

A.1.2.1 The residual compressive strength at each firing stage, the each percentage of addition is compared to the ambient temperature:

In comparison to ambient temperature, the residual compressive strength of GPC mixtures including SF is displayed in Figure(6). The decrease in compressive strength of specimen G1-0%SF relative to its compressive strength at ambient temperature are (6% ,52%, 63%) at (250˚c,500˚c,750˚c) respectively. While the specimen G2-0.5%SF which contains (0.5%)of steel fiber , decreasing in compressive strength shows(9%, 33%, 60%) at(250˚c, 500˚c,and 750˚c) respectively. The increase steel fiber percentage to (0.75%) in the specimen G3-0.75%SF, can notice the decrease in compressive strengths are (7%,34%,52%) at (250˚c,500˚c,750˚c) respectively. While when steel fiber percentage becomes (1%) at the specimen G4-1.0%SF shows (8%, 38%,50%) at (250˚c,500˚c,750˚c) respectively.



Figure(6) The impact of SF on residual compressive strength at various temperatures

A.1.2.2 The residual compressive strengths at each a volumetric ratios (SF) for each firing level is compared:

The Table(10) show the comparison the GPC specimens relative to specimen G1-0%SF which contains 0%SF at different fire temperature. The residual compressive strength slightly improved by increasing volumetric ratio of steel fiber. At 250˚c, the enhancement show in the residual compressive strength compares to the mix G1-0%SF are (17%,34% ,57%) for mixes (G2-0.5%SF, G3-0.75%SF, G4-1.0%SF) respectively. The bond between the SF and the geopolymer concrete is strengthened because of the continuous polymerization at 250ºC, which densifies the microstructure of the geopolymer.

As a rule, at 500˚c and at 750˚c , the G1-0%SF mixes(without SF) start to lose its compressive strength as shown in Figure(7) . When, the temperature increase to 500˚c can be noticed , the residual compressive strengths results compared relative to specimen G1-0%SF are (68%,87%, 109%) for mixes (G2-0.5%SF,G3-0.75%SF, G4-1.0%SF) respectively . It can be see the slightly enhancement in residual compressive strength. From comparison shows the specimen G4-1.0%SF have higher residual compressive strength.

AT 750˚c of fire exposure, it can be see the enhanced in residual compressive strength relative to mix G1-0%SF by (28%,74%,113%) for specimens (G2-0.5%SF, G3-0.75%SF, G4-1.0%SF) respectively. From the description above, it can be determined that adding 1.0% of volumetric ratio SF results in improved fire resistance.

Table (10) Residual compressive strength at different fire temperature

Mix Designation	SF %	Compressive Strength (MPa)			Increasing in Compressive Strength (%)		
		250 ˚c	500 ˚c	750 ˚c	250 ˚c	500 ˚c	750 ˚c
G1-0.0%SF	0	30.1	15.3	12.01	-	-	-
G2-0.5%SF	0.5	35.3	25.7	15.4	17	68	28
G3-0.75%SF	0.75	40.3	28.65	20.9	34	87	74
G4-1.0%SF	1	47.3	32	25.6	57	109	113

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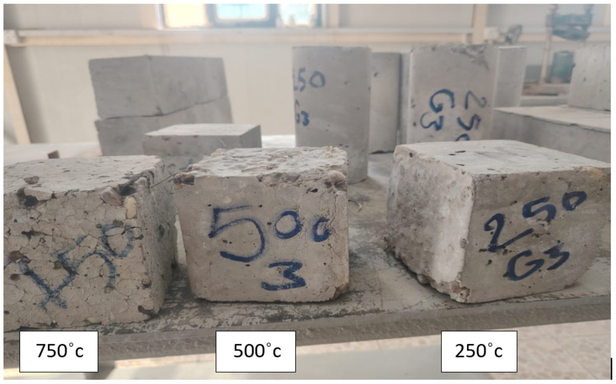


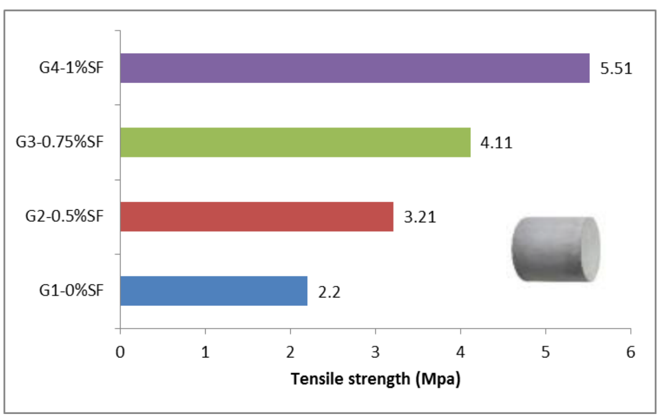
Figure (7) Examples of cubic specimens after exposed 750˚c

Figure(9) Damage patterns of specimens after cylinder tensile strength test

A.2 Tensile Strength

A.2.1 Effect of Steel Fiber at Ambient Temperature

Figure(8) shows the enhancement in tensile strength by increasing the volumetric ratio of steel fiber. Steel fiber-incorporated geopolymer concrete specimens had a greater cylinder tensile strength than regular geopolymer concrete [32]. The increase in tensile strength for mixes (G2-0.5%SF ,G3-0.75%SF and G4-1.0%SF) at 0.5%, 0.75% and 1.0% of SF was 46%, 87% and 150%, respectively. The maximum splitting tensile strength is 5.51 MPa When steel fiber content is 1.0%, and the lowest value is 3.21 MPa at 0.5% content, this is still more than that of the geopolymer concrete without steel fibres. The steel fibers that are incorporated into the geopolymer concrete successfully change its tensile behavior. Figure (9) shows the GPC specimens after splitting tensile strength.



Figure(8) Results the splitting tensile strength at ambient temperature

A.2.2 Effect of Steel Fiber at Elevated Temperature After Fire Exposure

The GPC tensile strength of the heated specimens decreased significantly and steadily as the heating temperature raised. The splitting tensile strength of geopolymer concrete is directly correlated with its steel fiber content, and it rises as the steel fiber content does[33]. Furthermore, there was no brittle fracture in the geopolymer concretes that contained steel fibers.

A.2.2.1 Residual tensile strength at different fire temperature is compared relative to ambient temperature

From the result as shown in Figure(10) all specimens decreased in tensile strength relative to ambient temperature as same as behavior in compressive strength. The decrease in tensile strength for specimen G1-0%SF, relative to ambient temperature are (14%,36%,50%) at (250˚c,500˚c and 750˚c)respectively. By increasing the percentage of steel fiber to 0.5% in specimen G2-0.5%SF, can be see the decreasing in residual tensile strength relative to ambient temperature are (14%,22%,53%) at (250˚c,500˚c and 750˚c)respectively. While in specimen G3-0.75%SF , it can be noticed that the GPC tensile strength decreased by (10%,23%,28%) at (250˚c,500˚c and 750˚c)respectively. The G4-1%SF mix can bear residual compressive strength up to 26 %, 31 %, 40 %, and 41 % for 250oc, 500Oc and750oc, of fire exposure. The compared shows decreasing in tensile strength at increasing the fire temperature.

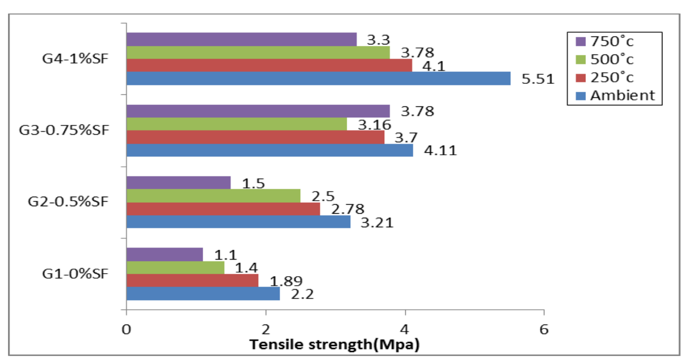


Figure (10) Effect of steel fiber on residual tensile strength at different fire temperature

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A.2.2.2The residual tensile strength at each percent of (SF) for each degree of fire temperature is compared:

Table (11) shows the results of the splitting tensile strength test. It can be inferred that the splitting tensile strength increases with the increase in the steel fiber percentage. In this paragraph seen the comparison the GPC mixes at different fire temperature relative to mix G1-0%SF. At 250˚ the increasing in tensile strength compared with specimen G1-0%SF are (47%, 95%, 117%) for specimen (G2-0.5%SF, G3-0.75%SF and G4-1%SF) respectively. From compared above can be see the residual tensile strength at 250˚c is behavior similar to behavior in compressive strength.

When, the temperature increase to 500˚c can be noticed , the residual tensile strengths are (1.4 Mpa, 2.5 Mpa, 3.16Mpa,3.78Mpa) for mixes (G1-0%SF-G2-0.5%SF- G3-0.75%SFand G4-1.0%SF) respectively. The results compared relative to specimen G1-0%SF are (79%,125%, 170%) for mixes (G2-0.5%SF- G3-0.75%SF-G4-1.0%SF) respectively .

Finally, at 750˚c the tensile strength is continuous in increasing relative to specimen G1-0%SF (without steel fiber). The increasing in residual tensile strength (36%,170%, 200%) for mixes (G2-0.5%SF- G3-0.75%SF-G4-1.0%SF) respectively . The maximum splitting tensile strength is 3.3 MPa when the steel fiber content is 1.0%, and the smallest is 1.5MPa at 0.5% content, it is remain greater than that of the geopolymer concrete with no steel fibers. The results showed that adding steel fibers caused an increasing in residual tensile strength.

Table (11) Residual tensile strength at different fire temperature

Mix Designation	Tensile Strength (MPa)			Increasing in Tensile Strength (%)		
	250 ˚c	500 ˚c	750 ˚c	250 ˚c	500 ˚c	750 ˚c
G1-0.0%SF	1.89	1.4	1.1	-	-	-
G2-0.5%SF	2.78	2.5	1.5	47	79	36
G3-0.75%SF	3.7	3.16	2.98	95	125	170
G4-1.0%SF	4.1	3.78	3.3	117	170	200

CONCLUSION

This research focuses about the mechanical characteristics of geopolymer concrete (GPC). The study's goal is to develop GPC under ambient conditions with good mechanical performance and fire resistance features, as well as three volumetric ratios of steel fibres (SF). The Mixtures are made to work the mechanical characteristics of GPC before and after fire exposure. The compressive strength, splitting tensile strength , residual compressive strength, and residual tensile strength are assessed for mixtures before and after exposure to three different fire levels (250,500,750)˚c. Many conclusions can be determined by the findings of this study.

1. The use of steel fibres considerably increased compressive strength and splitting tensile strength. These characteristics followed similar patterns once the steel fibers were added. Both strengths grew as the volume percentage of steel fibres increased, peaking when the steel fiber concentration reached 1.0%. The highest compressive tensile strength was 51.2 Mpa, and the highest value of tensile strength was 5.51Mpa.
2. The mechanical properties strength nearly keeps their ambient compressive strength for the mixes, whenever exposed to 250˚c of fire exposure.
3. The residual mechanical properties strength reduced with each subsequent firing from 250˚c to 750˚c relative to their strengths at ambient temperature.
4. Including SF considerably improved the GPC when subjected to various fire intensities, and the perfect addition ratio for the maximum residuals compressive strength and splitting tensile strength is 1%. Overall, it can be stated that the inclusion of SF considerably boosted the GPC under ambient and fire conditions.

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