Challenge Journal of Concrete Research Letters

Research Article

Effect of different fiber types on the mechanical properties of normal and high strength concrete at elevated temperatures

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ABSTRACT

The effects of the types of fibers on mechanical properties of normal and high strength concrete under high temperature, up to 700 °C, was investigated. Three different- type fiber; "Steel Fiber (SF), Glass Fiber (GF) and Polypropylene Fiber (PPF)" are added into the concretes in five different ratios (0, 0.50, 1.00, 1.50 and 2.0%)of the volume under the following temperatures; 22, 100, 400 and 700°C. The results indicate that all the different types of fibers researched contribute to both the compressive and flexural strengths of concrete under high temperature, however, it is also found that this contribution decreases with an increase in temperature. The flexural strengths and compressive strengths for NSC and HSC mixes at 28 days under high temperature decreases as the temperature increases especially up to 400°C. Also, the best compressive and flexural strengths performance under high temperature was also those of SF. The compressive strength of the concrete incorporating SF was reduced under high temperature only, while the mixes containing PPF and GF were reduced under high temperature or with fiber addition. The optimum fiber addition ratios of the mixes containing PPF and GF are between 0.5-1.0 percent by volume. And for SF, it is 1.5% by the volume.

ARTICLE INFO

Article history:
Received 20 August 2020
Revised 27 February 2021
Accepted 3 March 2021

Keywords:
Steel fiber
Polypropylene fiber
Glass fiber
Compressive strength
Flexural strengths
Elevated temperature

1. Introduction

Fiber reinforced concrete (FRC) may be defined as a composite material made up of cement and aggregate, while incorporating discontinuous fibers. Fibers play a role in is to increase the toughness of the concrete. That is, the fibers tend to increase the strain at peak load, and provide a great deal of energy absorption in the post-peak portion of the load vs. Deflection curve. In recent years, fiber reinforced concrete has become a new way to search and improve mechanical properties and durability of concrete (Juan-García et al., 2016; Zheng et al., 2020; Ghugal and Deshmukh, 2006; Peled et al., 2005; Purnell et al., 2000). Exposure to an elevated temperature may have adverse impacts on mechanical properties of concrete. For the plain concrete, the changes may happen in the pore structures that lead to spalling, cracking, and destroying the ligament between aggregates and cement paste and the decaying of hardening cement paste (Georgali and Tsakiridis, 2005). This process is defined as thermal incompatibility of concrete components and leads to two mechanisms that are the mechanism of build-up vapor pressure (Anderberg, 1997) or the restricted thermal dilatation (Bažant and Kaplan, 1996). Compared to NSC, HSC may be more susceptible to building up pressure that is due to its low permeability (Noumowe et al., 2009; Sanjayan and Stocks, 1993). The dense microstructure of HSC decreases the vapor water and liquid migration. Due to thermal incompatibility, thermal stresses are generated between the cement paste and the aggregate, leading to an induced stress which in turn causes the collapse of the interfacial bond between the aggregate and the cement dough leading to loss of strength (Cülfik and Özturan, 2010). If the concrete is submitted to the fire, free water may be removed in the concrete matrix during a physical process like

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ISSN: 2548-0928 / DOI: https://doi.org/10.20528/cjcrl.2021.01.004

evaporation at a lower temperature. With increase in temperature, hydrates disintegration and bonded water loss may occur. Calcium hydroxide decomposition happens approximately at 350°C, while partial volatilization of calcium silicate hydrate gel begins at 500°C. Pore size and porosity of the hydrate matrix may increase, and in turn, mechanical properties like strength and elastic modulus of the hydrates may be decreased. Moreover, the crystal structure of quartz, in a siliceous aggregate at 573 °C, converts from low temperature to a high-temperature phase. This change followed by a one percent volume increase; quickens the hydrates disintegration. All of these transformations make the mechanical properties of a heated concrete (in a macro-scale) depend on the temperature.

Cementitious structures are described as brittle, with decreasing in tensile and flexural strengths. The cementitious structures with fibers resist this weakness; produce the structures with high tensile strength, ductility, toughness and durability. The efficiency of the fibers depends on a multitude of factors including matrix properties, such as size, type, geometry, volume and dispersion of fiber (Kuder and Shah, 2010). Carbon fiber and glass fiber are incombustible materials, therefore their properties are different from polypropylene and polyvinyl alcohol fibers. For decreasing the propagation of crack and increasing the ductility of concrete, these fibers should be added to the concrete mixture. Carbon and glass fibers enhance the mechanical properties of concretes under high temperature that is due to their incombustible properties (Daniel et al., 2002; Pavlík et al., 2002; Şahmaran et al., 2011; Tanyildizi, 2008; Hilles and Ziara, 2019). Studies on the effect of elevated temperature on mechanical properties of fiber reinforced cementitious composites found that the flexural strength of mortar may be significantly improved by different fiber types, but the compressive strength of the mortar reduces under elevated temperatures (Çavdar, 2012; Cree et al., 2017; Mohammadhosseini et al., 2020; Raza et al., 2020).

Altun and Oltulu (2020) investigated the effect of different types of fiber utilization on mechanical properties of recycled aggregate concrete containing silica fume and the results showed that the compressive strength, flexural strength and impact resistance of RAC were reduced as the percentage of RCAs increased. Results of Zhong et al. (2020) showed that the reactive powder concrete ductility can be further improved on the basis of polypropylene fiber RPC, the compressive strength and splitting tensile strength of polypropylene fiber.

The main aim of the current study to investigate the impacts of the different fiber types on the mechanical properties of normal and high strength concretes at elevated temperature. Regarding the novelty of this paper, it is significantly original because it involved analyzing the behaviours of the normal and high strength concretes resulting represented in its compressive and flexural strengths at different degree of temperatures. The production of twenty-six concrete mixtures with three types of fibers and five ratios are made for this purpose. The mixes are submitted to four elevated temperatures. Steel Fiber (SF), Glass Fiber (GF) and Polypropylene Fiber (PPF) are selected for the fibers. These fibers are added to the concrete in five ratios (0, 0.5, 1.0, 1.5 and 2.0%) by volume. The concrete are subjected to elevated temperatures: 22, 100, 400 and 700°C. The mechanical properties investigated are compressive and flexural strengths of the concrete mixes.

2. Experimental Work

In this study, the known effects of the types of fiber on mechanical properties of normal and concrete of high strength under high temperature are investigated. The materials that are used in the present research were selected from local materials in Egypt.

2.1. Materials

Portland cement type CEM I–52.5 N was used in concrete mixes. In accordance with the Egyptian Standard Specification (ES: 4756/1 2013), the cement testing was achieved. The properties of the cement in use are shown in Table 1. Three different fiber types are used in the experimental work. The fibers are SF, GF and PPF. Table 2 reveals the fiber properties used in this work. The aggregates used in this research work consisted of local natural coarse aggregates (crushed dolomite) (4/19) mm with a specific density of 2.68 gm/cm^3, and maximum nominal size of 19 mm and natural siliceous sand (0/4) mm with a specific density of 2.65 gm/cm^3, and fineness modulus of 2.75. The coarse aggregate was washed about forty-eight hour before used and left to dry to prevent the impact of fine materials. According to Egyptian Standard (1109), testing of crushed dolomite and siliceous sand was performed. The silica fume that is used was locally produced in Egypt having 97.6% silica, and a bulk unit weight of 355 kg/m^3. A superplasticizer (SP) admixture of an aqueous solution of modified polycarboxylate basis was used. SP complies with ASTM-C-494 types F and G, with a specific density of 1.08 gm/cm^3.

Table 1. Physical and chemical composition of cementitious materials.

Properties	CEM I	Silica Fume
Physical		
Specific density (gm/cm^3)	3.14	2.13
Specific area (cm^2/gm)	3550	20500
Colour	Grey	Light Grey
Chemical compositions (%)		
Silicon dioxide ($SiO2$)	20.24	97.60
Calcium oxide (CaO)	62.23	0.25
Aluminium oxide (Al_2O_3)	5.91	0.18
Ferric oxide (Fe_2O_3)	3.34	0.45
Sulphur trioxide (SO_3)	2.19	0.10
Magnesium oxide (MgO)	2.15	0.55
Sodium oxide (Na_2O)	0.82	0.16
Potassium oxide (K_2O)	0.76	0.45
Loss on Ignition (LOI)	1.67	0.60

Table 2. Properties of the fiber types.

Properties	SF	GF	PPF
Length (mm)	15	15	15
Specific mass (kg/m^3)	7800	2600	900
Tensile strength (MPa)	2200	1600	400
Modulus of elasticity (MPa)	200000	71000	4000
Surface texture	Smooth	Grooved	Grooved
Absorption	None	Low	Low
Alkali resistance	High	High	High

2.2. Mix proportion

To achieve the aims of this work, two groups of concrete with a total number of 26 mixtures were prepared and investigated. Table 3 presented the mix design of all mixtures. The mixtures were grouped into two representing the variables in the study. The first group with 350 kg/m^3 cement content (mixes from M1 to M13), mix M1 possesses neither fibers nor silica fume (control mix), while the mixes from M2 to M13 contains three different fiber types with percentages of 0.5, 1.0, 1.5 and 2.0, and a water-cement ratio of 0.60 for mixes (M1 to M13). The second group with 450 kg/m^3 cement content (mixes from S1 to S13), mix S1 possesses neither fibers, while the mixes from S2 to S13 containing three different fiber types with percentages of 0.5, 1.0, 1.5 and 2.0. It contains also silica fume with a percentage of 15 and superplasticizer with a percentage of 3.0 as replacement of cement. The water to binder ratio was equal 0.25 for mixes (S1 to S13).

Table 3. Proportions of concrete mixtures.

Mix	CEM I (kg)	Sand (%)	Dolomite (%)	Silica fume (%)	Superplasticizer (%)	Water (w/b)	Fiber type (%)		
							SF	GF	PPF
M1	350	40	60	0	0	0.6	0	0	0
M2	350	40	60	0	0	0.6	0.5	0	0
M3	350	40	60	0	0	0.6	1.0	0	0
M4	350	40	60	0	0	0.6	1.5	0	0
M5	350	40	60	0	0	0.6	2.0	0	0
M6	350	40	60	0	0	0.6	0	0.5	0
M7	350	40	60	0	0	0.6	0	1.0	0
M8	350	40	60	0	0	0.6	0	1.5	0
M9	350	40	60	0	0	0.6	0	2.0	0
M10	350	40	60	0	0	0.6	0	0	0.5
M11	350	40	60	0	0	0.6	0	0	1.0
M12	350	40	60	0	0	0.6	0	0	1.5
M13	350	40	60	0	0	0.6	0	0	2.0
S1	450	40	60	15	3	0.25	0	0	0
S2	450	40	60	15	3	0.25	0.5	0	0
S3	450	40	60	15	3	0.25	1.0	0	0
S4	450	40	60	15	3	0.25	1.5	0	0
S5	450	40	60	15	3	0.25	2.0	0	0
S6	450	40	60	15	3	0.25	0	0.5	0
S7	450	40	60	15	3	0.25	0	1.0	0
S8	450	40	60	15	3	0.25	0	1.5	0
S9	450	40	60	15	3	0.25	0	2.0	0
S10	450	40	60	15	3	0.25	0	0	0.5
S11	450	40	60	15	3	0.25	0	0	1.0
S12	450	40	60	15	3	0.25	0	0	1.5
S13	450	40	60	15	3	0.25	0	0	2.0

2.3. Test procedures

The compressive strength test of concrete was tested using cubes (150 mm) according to BS 1881: part 116–2004, at the age of 28 days. The flexural strength test at 28 days was performed according to ASTM C78/C78M-16. The prism specimens of 100×100×500 mm for flexural strength were used. The density of concrete at 28 days was performed according to BS 1881: part 114–2004. An average of three specimens was recorded for each testing age and all strengths. The specimens of mixes were demolded 24 hours after the casting and placed in the standard water tank until testing at 28 days. After 28 days water curing, they were heated in an electric furnace up to 100, 400 and 700°C. Each temperature was maintained for 1.5 hours to achieve the thermal steady state. The specimens were allowed to cool naturally to room temperature.

3. Results and Discussion

The results of compressive strength, flexural strength and density of mixes under elevated temperatures are shown in Table 4.

Table 4. Properties of normal and high strength concrete at high temperature.

Mix	Compressive Strength (MPa)				Flexural Strength (MPa)				Density (kg/m^3)				Notes
	22°C	100°C	400°C	700°C	22°C	100°C	400°C	700°C	22°C	100°C	400°C	700°C	
M1	33.50	34.82	30.17	16.07	5.34	5.00	1.76	0.96	2260	2260	2170	2130	Control mix.
M2	34.85	38.68	33.46	19.51	5.71	6.68	3.71	1.55	2280	2280	2190	2165	SF-0.5%
M3	36.52	42.36	34.70	19.36	6.30	7.24	4.10	1.64	2300	2300	2208	2186	SF-1.00%
M4	37.86	42.40	35.59	19.68	6.89	8.00	4.41	1.73	2325	2325	2232	2209	SF-1.5%
M5	36.85	40.90	33.53	18.05	6.09	7.07	3.84	1.58	2350	2350	2258	2136	SF-2.00%
M6	28.80	31.40	23.05	12.10	5.50	6.44	2.59	0.83	2145	2145	2037	2017	GF - 0.5%
M7	27.47	31.32	18.41	10.44	5.67	6.35	2.22	0.63	2075	2075	1972	1950	GF - 1.00%
M8	25.12	27.90	11.30	6.28	5.08	5.90	2.29	0.56	1990	1990	1870	1832	GF - 1.5%
M9	23.45	27.44	8.68	4.69	4.55	5.00	2.14	0.46	1900	1900	1768	1713	GF - 2.00%
M10	30.51	32.65	23.50	11.60	5.66	6.68	2.61	0.85	2150	2150	2043	2025	PPF -0.5%
M11	28.13	30.40	20.25	10.41	6.00	6.78	2.16	0.84	2080	2080	1980	1958	PPF -1.00%
M12	26.80	29.50	16.10	10.71	5.35	6.10	1.72	0.59	2060	2060	1960	1937	PPF -1.5%
M13	25.13	29.15	12.10	7.54	4.92	5.41	1.48	0.50	2036	2036	1938	1915	PPF - 2.00%
S1	88.50	90.28	61.95	23.90	14.00	12.88	3.92	1.68	2340	2340	2246	2108	Control mix.
S2	91.16	101.19	82.05	44.66	14.84	17.21	9.35	3.71	2360	2360	2290	2264	SF-0.5%
S3	93.82	106.02	82.56	45.04	16.53	19.00	9.92	3.97	2385	2385	2312	2290	SF-1.00%
S4	98.23	111.98	87.43	46.17	17.64	20.11	10.6	4.42	2410	2410	2330	2314	SF-1.5%
S5	95.58	106.10	83.16	42.06	16.10	18.19	9.67	3.87	2430	2430	2357	2330	SF-2.00%
S6	77.89	84.12	62.32	31.16	14.28	16.57	6.34	2.00	2245	2245	2155	2130	GF - 0.5%
S7	74.34	84.74	47.58	26.77	14.72	16.34	5.74	1.62	2175	2175	2087	2065	GF - 1.00%
S8	68.15	75.00	28.63	15.68	13.17	12.38	5.80	1.32	2100	2100	1996	1950	GF - 1.5%
S9	63.73	72.02	21.03	11.47	11.64	12.57	5.24	1.17	2016	2016	1894	1833	GF - 2.00%
S10	82.31	88.90	60.09	30.46	14.71	17.06	6.62	2.06	2250	2250	2160	2139	PPF -0.5%
S11	76.11	82.20	53.30	26.63	15.55	17.42	5.44	2.02	2180	2180	2095	2070	PPF -1.00%
S12	73.46	79.34	41.87	25.00	13.86	15.94	4.30	1.39	2155	2155	2070	2048	PPF -1.5%
S13	69.03	78.70	31.06	18.64	12.75	14.03	3.57	1.28	2130	2130	2045	2024	PPF - 2.00%

3.1. Compressive strength

The comparison between non-fibrous concrete and mixes incorporating with three distinctive fiber types subjected to four different temperatures. Fig. 1 and Table 4 show the compressive strength of the normal strength concrete mixes under high temperature. It can be seen that the compressive strength of non-fibrous concrete decreases as the temperature increases. The compressive strength of non-fibrous concrete reduces approximately 10% at 400°C and about 52% at 700°C. Compressive strength of SF concrete mix reduces about 10% at 400°C (SF-2.0%) and on average 52% at 700°C (SF-2.0%). While GF, the reduction are about 63% at 400°C (GF-2.0%) and on average 80% at 700°C (GF-2.0%). And for PPF, the reduction is about 52% at 400°C (PPF-2.0%) and about 70% at 700°C (PPF-2.0%). Fig. 2 and Table 4 show the compressive strength of the high strength concrete mixes under high temperature. For non-fibrous concrete, it can be seen that the compressive strength of decreases as the temperature increases. The compressive strength of HSC without fibers decreases on average 30% at 400°C and about 72% at 700°C. The compressive strength of HSC with SF reduces about 13% at 400°C (SF-2.0%) and on average 56% at 700°C (SF-2.0%). But GF, the reduction is about 67% at 400°C (GF-2.0%) and on average 82% at 700°C (GF-2.0%). And for PPF, the decreases are on average 55% at 400°C (PPF-2.0%) and about 73% at 700°C (PPF-2.0%).

The difference between the compressive strength test for normal or high strength concrete (non-fibrous concrete and mixes incorporating with three different fiber types subjected to four different temperatures) is shown in Figs. 3 and 4. Decreases in compressive strength remain at a reasonable level for up to 1.0% fiber addition for each temperature, for all types of fibers. Elevated temperatures, decay the concrete by changing the cement paste hydration. Because of the ductile structure of the fibers compared to the concrete and having the cause of the concrete discontinuity, they are added in the normal strength concretes or high strength concretes. This helps in reducing the compressive strength. According to the samples investigated under dry conditions, around 100°C, fibers revealed better performance comparing to those of wet conditions (22°C). The references show that the melting of fibers at elevated temperatures form gaps that meet the vapor pressure. The findings of the compressive strength at elevated temperatures for all mixes are consistent with the results in the studies of Cülfik and Özturan (2010), Çavdar (2012), Amin et al. (2020), and Mohammadhosseini et al. (2020).

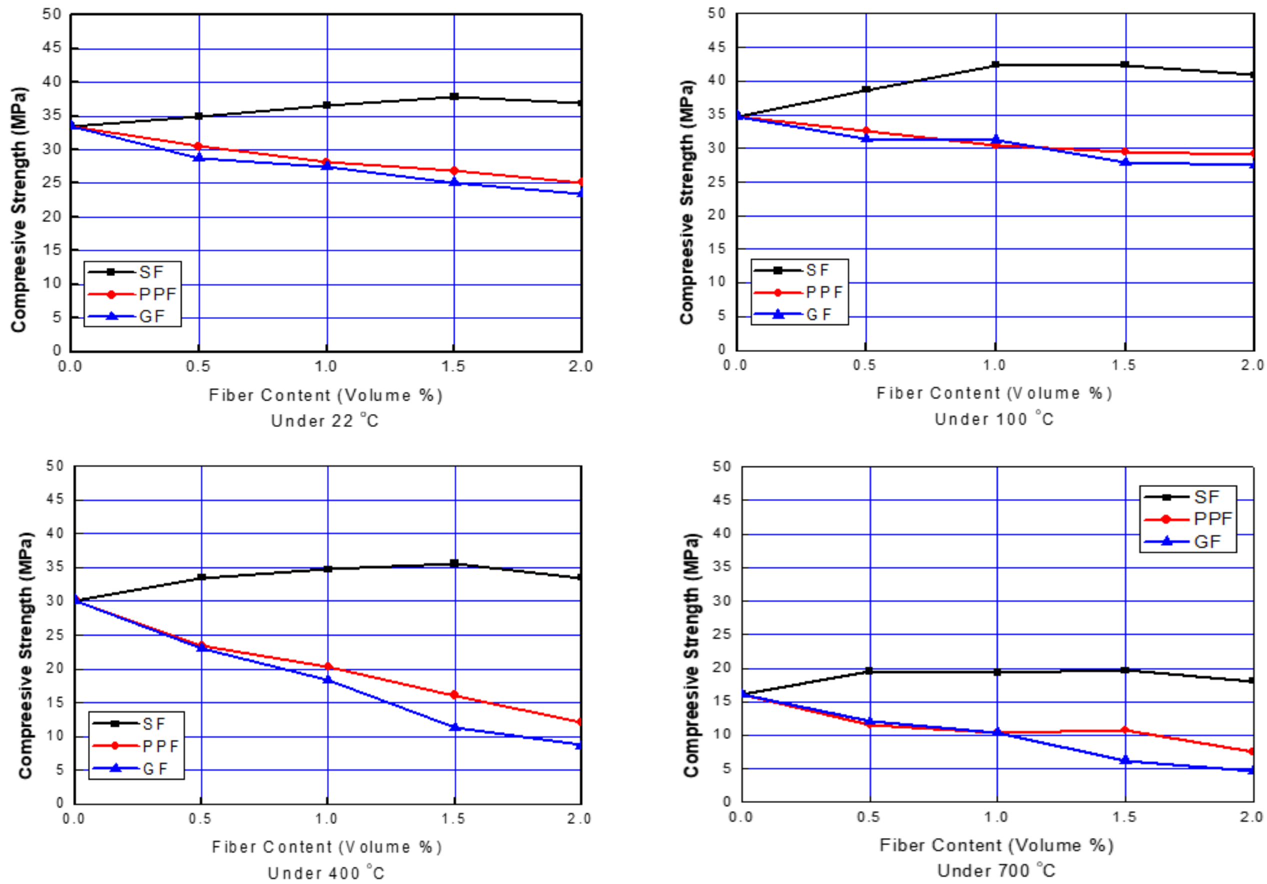

Fig. 1. Effect of fiber content on compressive strength at high temperature (normal strength concrete).

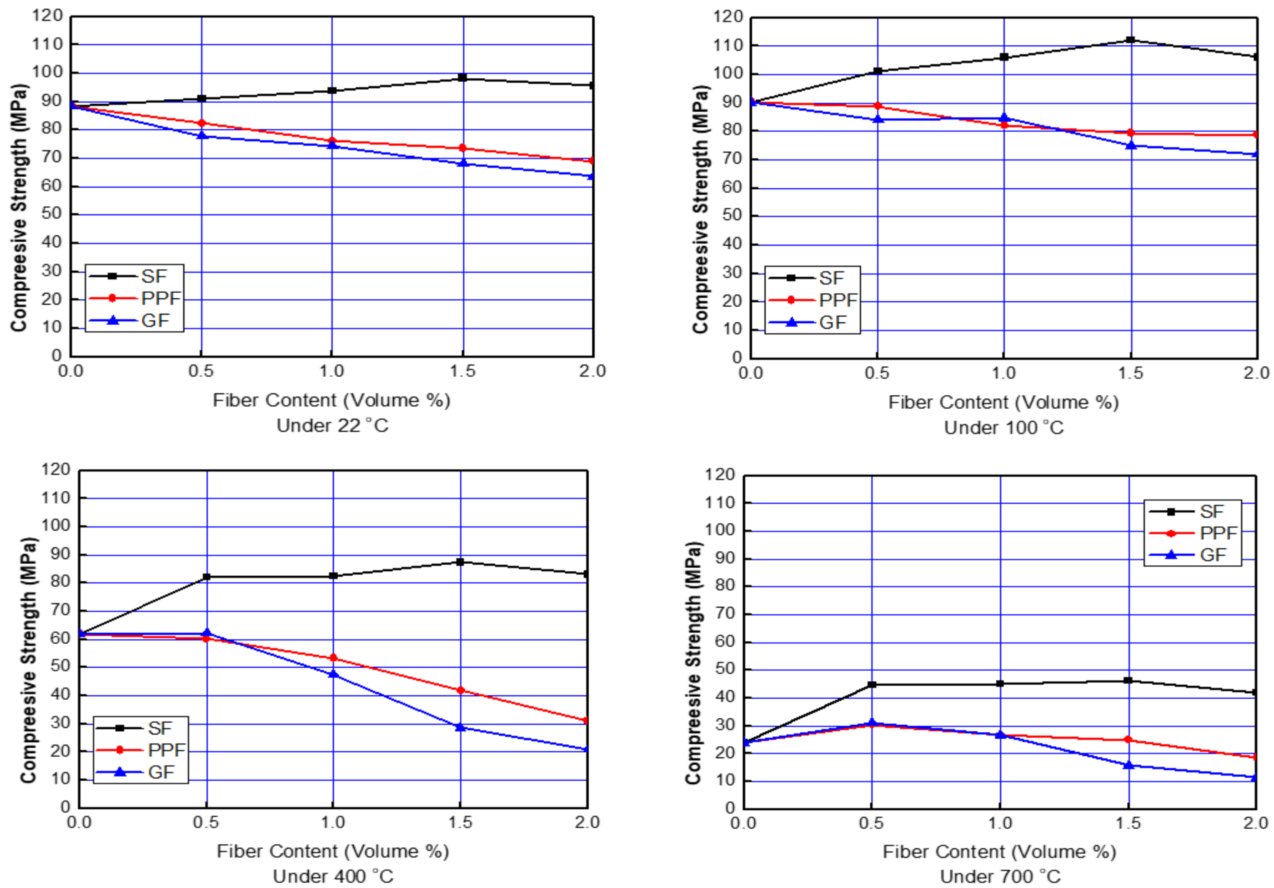

Fig. 2. Effect of fiber content on compressive strength at high temperature (high strength concrete).

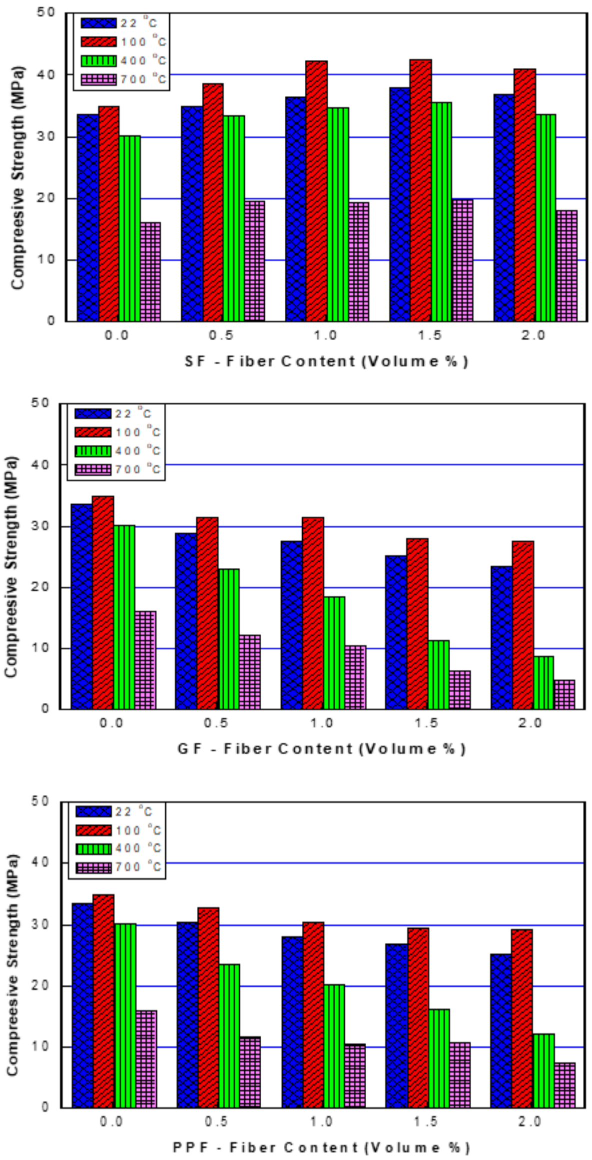

Fig. 3. Effect of fiber content on compressive strength at different temperatures (normal strength concrete).

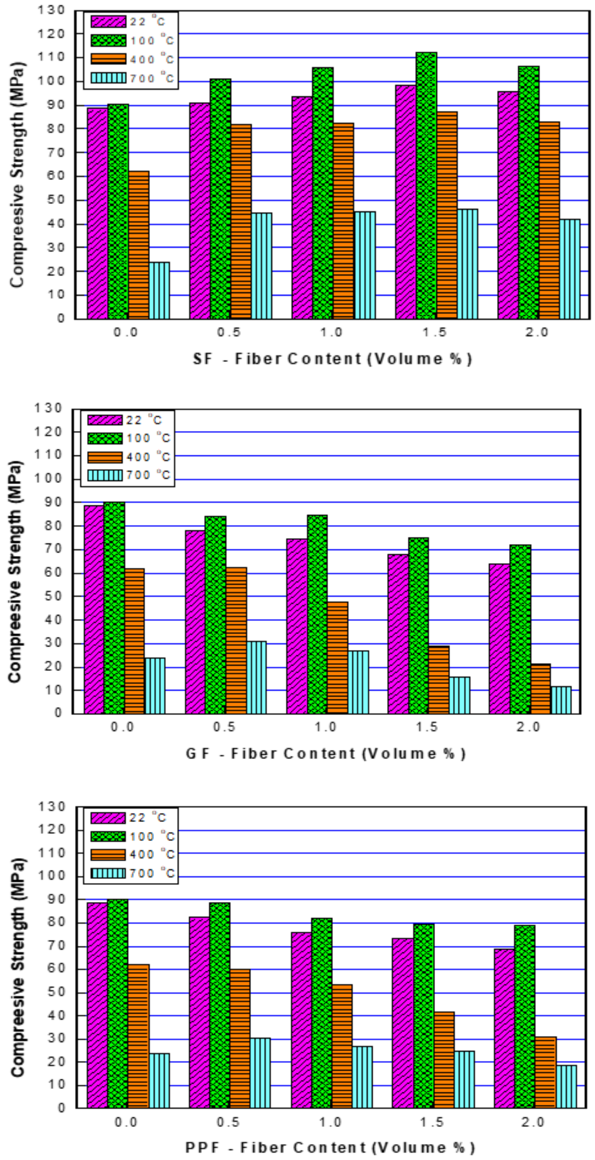

Fig. 4. Effect of fiber content on compressive strength at different temperatures (high strength concrete).

3.2. Flexural strength

The comparison between non-fibrous concrete and mixes incorporating with three distinctive fiber types subjected to four different temperatures. Fig. 5 and Table 4 show the flexural strength of NSC mixes under elevated temperature. When the temperature increases, the flexural strength of non-fibrous concrete reduces. The flexural strength of NSC without fibers reduces on average 67% at 400°C and about 82% at 700°C. The flexural strength of SF concrete mix reduces about 37% at 400°C (SF-2.0%) and on average 75% at 700°C (SF-2.0%). For GF, the reduction is about 53% at 400°C (GF-2.0%) and on average 90% at 700°C (GF-2.0%). According to PPF, the average decrease is 70% at 400°C (PPF-2.0%) and around 90% at 700°C (PPF-2.0%). Fig. 6 and Table 4 shows the flexural strength of HSC mixes under high temperature. It is observed that the flexural strength of non-fibrous concrete reduces when the temperature increases. The flexural strength of concrete without fibers reduces on average 72% at 400°C and about 88% at 700°C. The flexural strength of HSC with SF reduces about 40% at 400°C (SF-2.0%) and on average 76% at 700°C (SF-2.0%). While, GF mix, the reduction is on average 55% at 400°C (GF-2.0%) and about 90% at 700°C (GF-2.0%). And For PPF, the reduction is about 72% at 400°C (PPF-2.0%) and on average 90% at 700°C (PPF-2.0%).

Comparison between the results of the flexural strength for NSC and HCS (non-fibrous concrete and mixes incorporating with three different fiber types subjected to elevated temperatures from 22 to 700°C) are shown in Figs. 7 and 8. All types of fibers supply the concrete with the flexural strengths under high temperature. However, this supplying reduces while temperature increases. The decreasing of flexural strength of the concrete is due to the decomposition of calcium that depends on binding minerals of the concrete under elevated temperature (400°C and 700°C). The results are according to those in the studies of Çavdar (2012), Amin et al. (2020), and Mohammadhosseini et al. (2020).

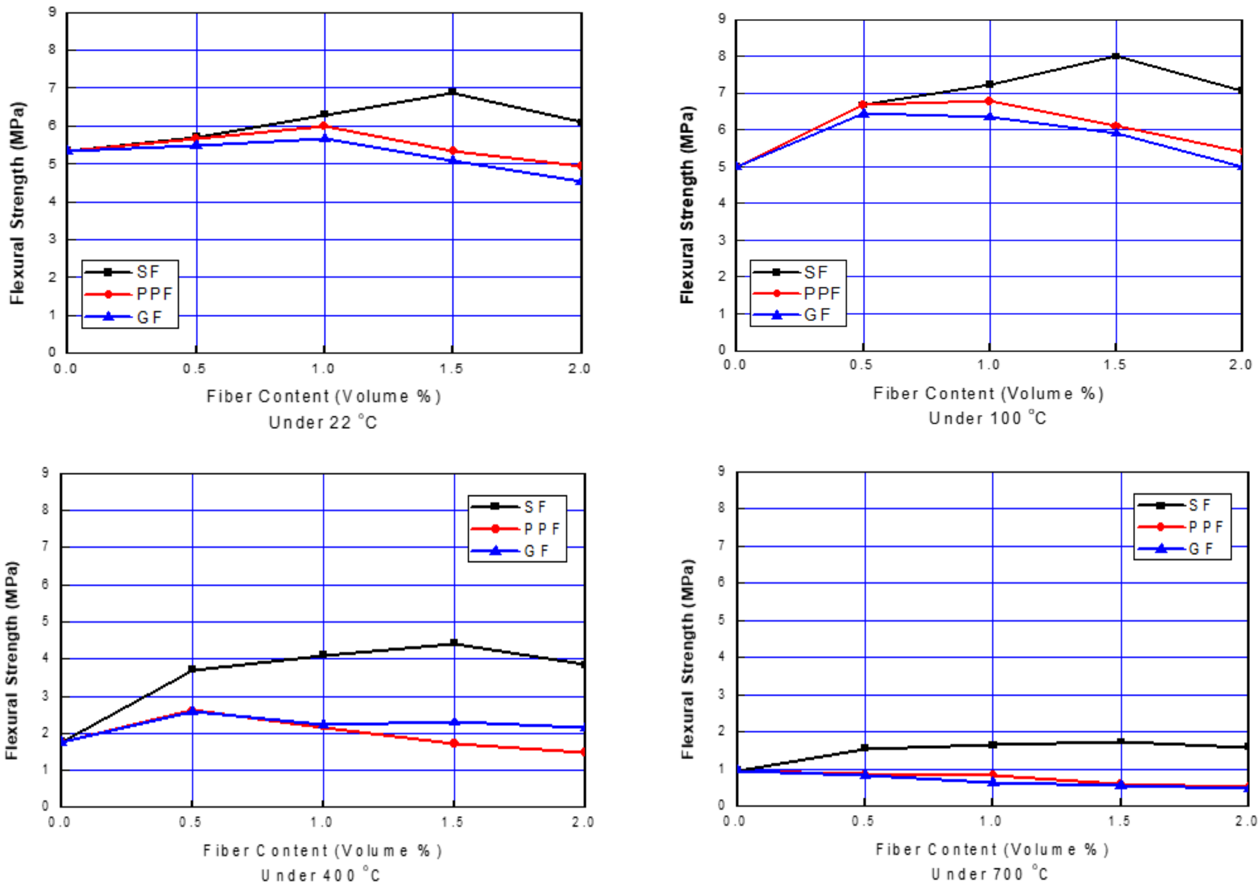

Fig. 5. Effect of fiber content on flexural strength at high temperature (normal strength concrete).

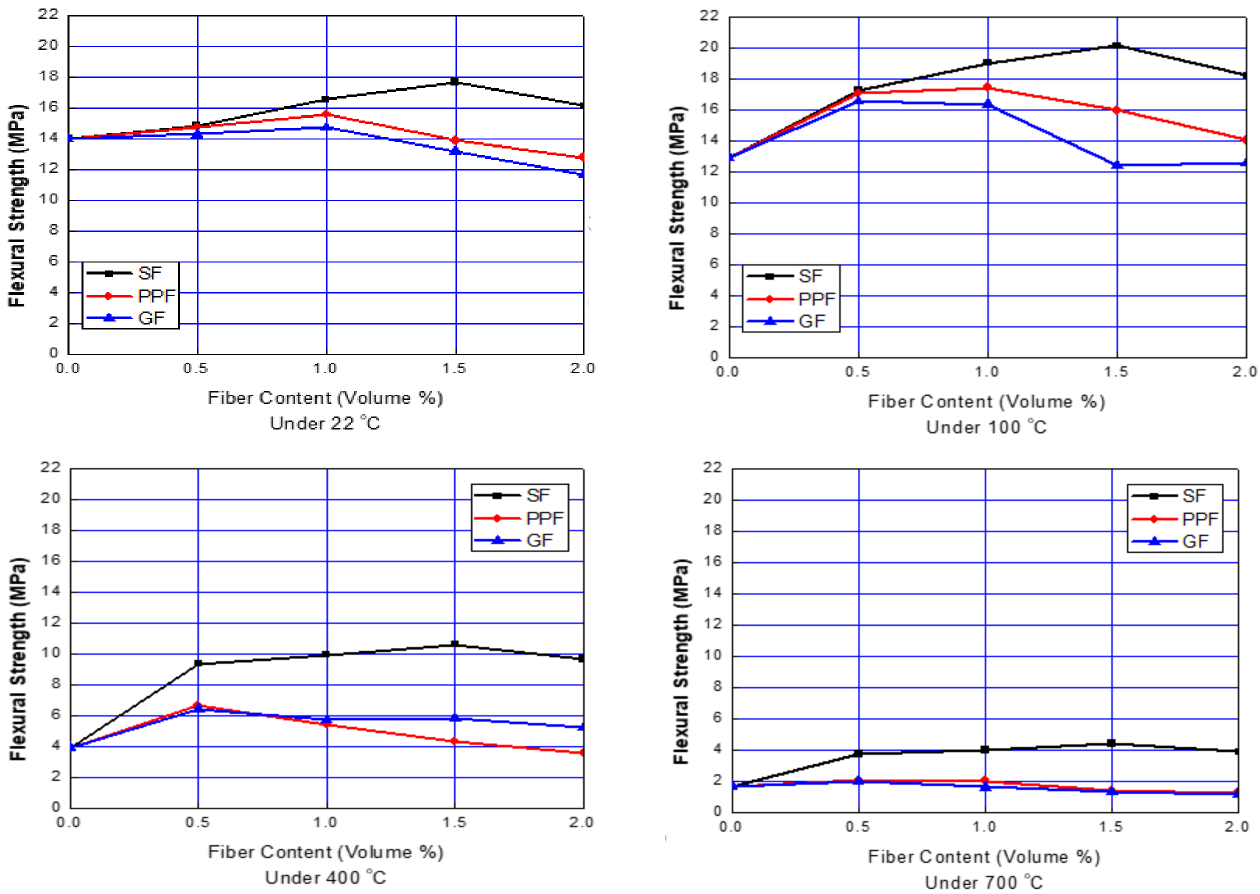

Fig. 6. Effect of fiber content on flexural strength at high temperature (high strength concrete).

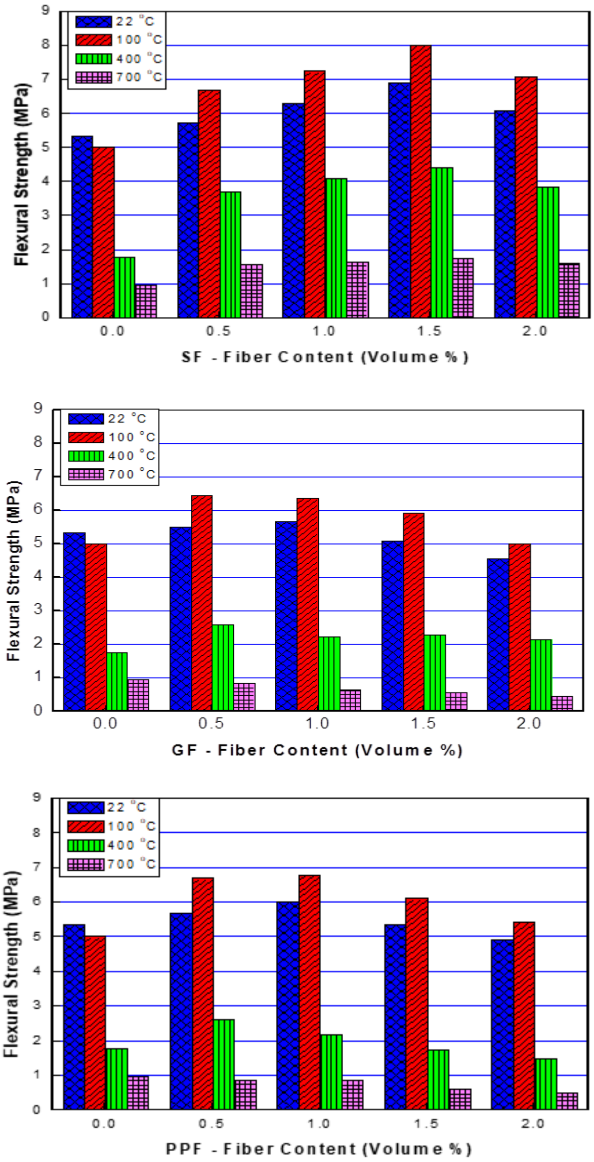

Fig. 7. Effect of fiber content on flexural strength at different temperatures (normal strength concrete).

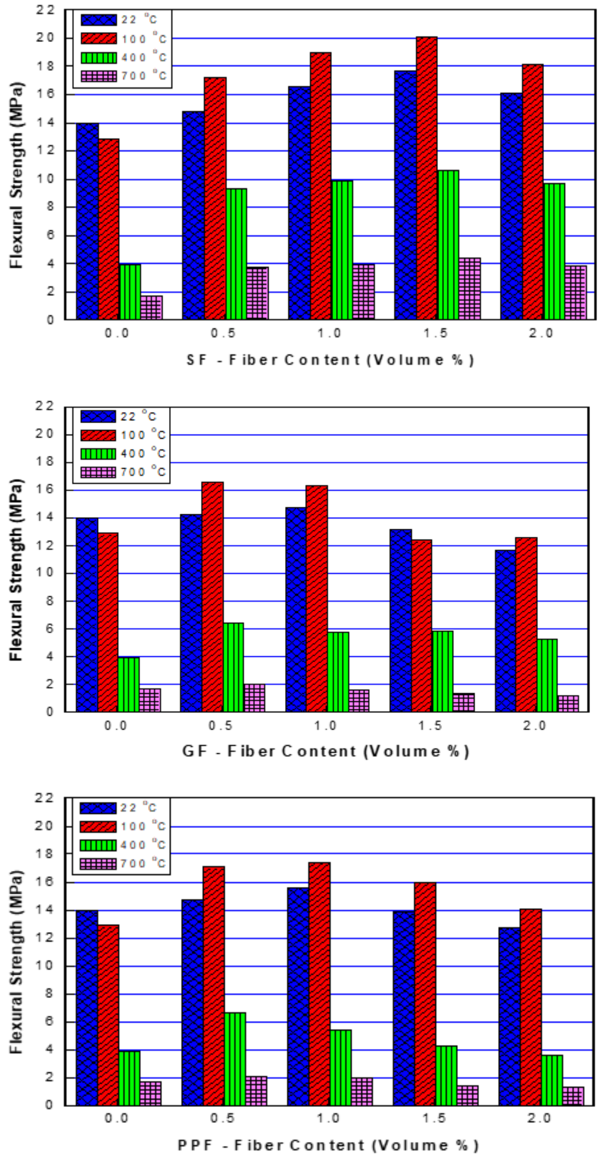

Fig. 8. Effect of fiber content on flexural strength at different temperatures (high strength concrete).

4. Conclusions

Based on the results found and reported, the following observations can be made:

- A slight reduction in the compressive strength and flexural strength of all mixtures was noted at the elevated temperature by adding used fibers. Despite the higher losses in the density of mixtures than those of control mix, the losses in compressive and flexural strengths values of mixes were considerably lower at elevated temperatures. However, beyond 400°C, the drop in strength values was more evident.
- With elevated in temperature, many changes happen in concrete of normal and high strength mixes. At 400°C, some cracks and deteriorations happen in matrices, while at 700°C, the cement matrices are weakened, and cracked.
- The compressive strength of non-fibrous normal strength concrete reduces about 10% at 400 °C and about 52% at 700°C. The compressive strength of the normal strength concrete with SF reduces about 10% at 400°C (SF-2.0%) and about 52% at 700°C (SF-2.0%). For GF, the reduction is about 63% at 400°C (GF-2.0%) and on average 80% at 700°C (GF-2.0%). And For PPF, the reduction is on average 52% at 400°C (PPF-2.0%) and about 70% at 700°C (PPF-2.0%).
- The compressive strength of HSC without fibers reduces on average 30% at 400°C and about 72% at 700°C. The compressive strength of HSC with SF reduces on average 13% at 400°C (SF-2.0%) and about 56% at 700°C (SF-2.0%). For GF, the reduction are about 67% at 400°C (GF-2.0%) and on average 82% at700°C (GF-2.0%). And For PPF, the reduction is on average 55% at 400 °C (PPF-2.0%) and about 73% at 700°C (PPF-2.0%).
- The flexural strength of NSC without fibers decreases about 67% at 400°C and about 82% at 700°C. The flexural strength of the normal strength concrete with SF reduces about 37% at 400°C (SF-2.0%) and

about 75% at 700°C (SF-2.0%). For GF, the reduction is on average 53% at 400°C (GF-2.0%) and about 90% at 700°C (GF-2.0%). And For PPF, the reduction is about 70% at 400°C (PPF-2.0%) and on average 90% at 700°C (PPF-2.0%).

- The flexural strength of high strength concrete without fibers reduces about 72% at 400°C and about 88% at 700°C. The flexural strength of the high strength concrete with SF reduces on average 40% at 400°C (SF-2.0%) and about 76% at 700°C (SF-2.0%). For GF, the reduction is on average 55% at 400°C (GF-2.0%) and about 90% at700 °C (GF-2.0%). And for PPF, the reduction is on average 72% at 400°C (PPF-2.0%) and about 90% at 700°C (PPF-2.0%).
- The flexural strengths and compressive strengths for NSC and HSC mixes at 28 days under high temperature decreases as the temperature increases especially up to 400°C.
- Each fiber shows the best performance at different addition ratios when flexural and compressive strength are taken into consideration along with temperature. The highest increase in flexural strength and lowest decrease in compressive strength is at 0.5–1.5% fiber addition ratio for PPF and GF if all temperature conditions are taken into consideration. And for SF, it is 1.5% by volume.

Acknowledgements

Authors would like to thank Delta University for Science and Technology and Suez University for the support provided for this research.

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