Research Article

Mohammed Hadeed, Abeer M. Humad, and Majid Al-Gburi*

Utilization of hybrid fibers in different types of concrete and their activity

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Abstract: In this work, the influence of using hybrid fibers on the mechanical properties of two types of concrete: high-strength concrete (HSC) and lightweight concrete (LWC) was studied. Using hybrid fibers instead of using only one type reduced the negative effect on concrete mechanical performance. The glass fiber (GF) and polypropylene fiber (PPF) were used in different contents ranged from 0.2 to 1% as weight % of binder content. Moreover, combinations of both fibers "GF + PPF" were used in contents % of "0.3 + 0.5%," "0.5 + 0.5%," "0.3 + 1%," and "0.5 + 1%." LWC mixes were prepared by replacing 40% of the coarse aggregate of reference mix with volcanic material (pumice) as a volumetric replacing. To produce HSC, the water-to-cement ratio was reduced to 0.3, 10% silica fume was added, and 1% super plasticizer was used to obtain the consistency. Compressive strength, splitting strength, and flexural strength tests were carried out. The results showed that using 0.7% GF displayed the highest increases in compressive, splitting tensile, and flexural strength of HSC and LWC mixes. Furthermore, GF exhibited better performance and higher values in compressive, splitting tensile, and flexural strength tests in comparison with PPF. The optimum hybrid fiber content displaying the highest increment of all tested properties in both concrete types, HSC and LWC, was "0.5% GF + 0.5% PPF."

Keywords: hybrid fibers, mechanical properties, concrete mixes

*** Corresponding author: Majid Al-Gburi,** Structural and Fire Engineering Department, Luleå University of Technology, Luleå, Sweden, e-mail: majid.al-gburi@ltu.se
Mohammed Hadeed: Department of Building and Construction Engineering, Northern Technical University, Mosul, Iraq
Abeer M. Humad: Civil Engineering Department, College of Engineering, University of Babylon, Babil, Iraq

1 Introduction

Concrete is one of the most commonly used building materials in construction around the world due to easily molded to any anticipated durable structural shape. Nowadays, steel bars in reinforced concrete were replaced by different other materials such as short fibers [1–3]. Many properties of concrete can be improved by adding fibers such as strength and ductility. Moreover, adding fibers to plain concrete showed controlling shrinkage cracking and improved the tensile properties of concrete matrix [4,5]. ACI Committee [6] defines "fiber-reinforced concrete" (FRC) as "hydraulic cement concrete incorporating fine or fine and coarse aggregates and irregular discrete fibers," the fibers could be steel, plastic, glass or natural materials, and all have been used in concrete in various forms and sizes [6]. The randomly oriented fibers prevent the micro-cracking mechanism and limit crack propagation. Adding short discrete fibers to the concrete mixture improved the compressive strength, durability, tensile strength, flexural strength, and impact strength by producing a homogeneous and isotropic matrix [1,2,7].

Murthy *et al.* [7] recognized that replacing fine aggregate by using 25 μm and 5 cm long glass fiber (GF) up to 1.5% in normal grade concrete caused boosting in the mechanical strength. Moreover, Sangeetha and Sumathi [8] investigated using glass fiber in reinforced polymer concrete of 42 concrete columns; the results showed increasing in strength and ductility of concrete columns. Kumar *et al.* [9] utilized GF in geopolymer concrete composites based on fly ash and alkaline liquid; the test results of mechanical properties observed higher strength in less curing time compared with the Portland cement concrete.

Fauzan *et al.* [10] stated that high-strength concrete (HSC) is mainly a brittle material, with low tensile strength, utilizing steel fibers from waste tiers improved this brittleness, and enhanced tensile strength and other mechanical properties.

Polypropylene fibers (PPF) belong to the modern generation of large-scale, it comes in the fourth largest volume production just after polyesters, polyamides and acrylics manufactured chemical fibers. Polypropylene fiber has low density equal to (0.9 g/cc), moreover, it has high crystalline, high stiffness and excellent bacterial/chemical resistance, therefore, its commonly used in many industrial applications such as industrial ropes, packaging materials and furnishing product [11].

In fiber high-strength concrete (FHSC), fibers improved toughness in compression by decreasing the rapid and explosive failure risk under the static loading as well as energy absorption under the dynamic loading [12]. Where using polypropylene macro fibers in high performance concrete column succeeded to reduce the fragility and shrinkage. The matrix parameter of fibers in concrete like material type, geometry, proportion of adding, orientation, and fiber distribution, effect the properties and performance of fiber reinforced concrete [13]. The volume fraction and specific surface area should be considered as the most affected important parameters in fiber reinforced concrete, as well as the aspect ratio, which is defined as the fiber length divided by its equivalent diameter [14].

1.1 Hybrid FRC

When two or more types of fibers are intelligently combined to produce a composite that composite is called a hybrid or hybridization. Concrete is a complicated material with multiple phases ranging in size from microns to millimeters to centimeters, such as C–S–H gels, sand, and gravel consequently. Reinforcing concrete with single type of fiber can improve characteristics to a certain amount [12]. Whereas the hybrid fibers can provide more worth able technical qualities by incorporating of two or more different types of fibers into a common cement matrix to improve the overall properties of concrete in comparison with presence of single fiber [14]. Moreover, reinforcing the concrete by using hybrid fiber gives the opportunity to design a stronger, stiffer, more flexible, and ductile system to improve the first crack resistance in the post-cracking zone and ultimate strength in comparison with single FRC [15,16]. The presence of three-fiber hybrid increased compressive strength till 85 MPa and increased flexural toughness in comparison with the control mix [17].

Since using recycled aggregates in normal concrete exhibited increasing shrinkage, porosity and decreasing the mechanical properties in comparison with that of normal concrete [18] investigated adding polypropylene and steel fibers to recycled aggregate concrete to enhance these mechanical properties. Where the researchers produced recycled aggregate concrete containing 30%, 50% recycled coarse aggregate gained from the demolished buildings. The results showed that the compressive strength increased with the addition of 1% steel fiber in the recycled aggregate concrete. While the flexural and impact performance of steel FRC was improved as the volume fractions of steel fiber increased. Moreover, using the hybrid FRC presented the best results in their mechanical performance [18].

Moreover, Tayeh and Agwa produced light weight aggregate concrete contained 65% pumice lightweight coarse aggregate by using different curing condition with elevated temperatures from ambient temperature to 200°C, 400°C, and 600°C for 2 h of exposure time. The results showed that flexural and tensile strengths increased by 53% and 38% for mixtures containing 0.4% glass fiber. However, the compressive and flexural strengths of the lightweight concrete (LWC) that exposed to elevated temperature improved by adding glass fiber and PPF due to fixing the pores and cracks that formed in the concrete structure [19].

In recent years, hybrid fiber has been considered one of the most favorable materials for strengthening and repairing concrete constructions. In general, plain concrete has poor tensile strength and low crack resistance. Fiber hybridization uses various fibers types to support the resistance of these cracks in concrete construction.

The main goal of this article is to study the consequence presence of hybrid fibers in LWC and HSC mixtures and study the progress in strength compared with using single fiber and reference mixes for each concrete type. Twenty-five concrete mixes were casted, and compressive strength, splitting tensile, and flexural strength were tested.

2 Materials' specifications

The materials utilized in this article were as follows.

2.1 Cement

The cement that used in this study was Ordinary Portland Cement (OPC-Type1), provided from Badoosh Cement Factory's. Tables 1 and 2 show the physical, mechanical, and chemical characteristics of the cement, following the Iraqi Standards and Specifications (IQS) [20].

Table 1: Physical and mechanical characteristics of cement

Characteristics	Test results of cement used	IQS, No. 5 [20,25]
Specific surface area, Blaine method	2,800	>2,300 cm^2/g
Standard consistency, (%)	27.5	—
Setting time, Vicat device		
Initial setting, (min)	137	>45 min
Final setting, (min)	165	<600 min
Fineness on sieve No. 170, (%)	3	<22%
Compressive strength of 50 mm cubic mortar samples, (N/mm^2)		
3 days	23.8	>15 N/mm^2
7 days	29.6	>23 N/mm^2
Tensile strength, (N/mm^2)		
3 days	1.63	>1.6 N/mm^2
7 days	2.48	>2.4 N/mm^2

Table 2: Chemical analysis of cement

Compound composition	(%) cement used	IQS, No. 5 [20] (%)
Al_2O_3	5.80	3.0–8.0
SiO_2	21.35	17.0–25.0
$Fe2O_3$	2.60	0.5–6.0
CaO	62.30	60.0–67.0
SO_3	2.50	2.5–2.8
MgO	3.33	Not more than 5%
C_3S	34.50	31.3–41.05
C_2S	28.00	28.61–37.9
C_3A	10.20	11.96–12.3
C_4AF	7.82	7.72–8.02

2.2 Coarse aggregate

The washed rounded coarse aggregates that used in this study were provided from Al-Mosul city, Iraq, with the maximum aggregate size of 12.5 mm. Table 3 shows the results of the sieve analysis of the coarse material used. The aggregate percentage passing of coarse aggregate utilized, as shown in Table 3, was within the 5–14 mm (Fine) requirements of the British Standard [21]. The coarse aggregate utilized had a specific gravity of 2.66 and an absorption capacity of 0.4%, respectively.

Table 3: Sieve analysis of the used coarse aggregate

Sieve size (mm)	Passing (%)	BS standard [21]		
		Fine	Medium	Coarse
14	100	90–100	40–80	25–55
10	84.30	50–85	30–60	10–40
4.75	8.60	0–10	0–10	0–5
2.36	0.0	—	—	—

2.3 Fine aggregate

Natural sand was used in all concrete mixes, as fine aggregate, with a maximum size of 4.75 mm collected from the Khazer region in Mosul, Iraq. Table 4 shows the sieve analysis of the sand utilized following the BS 882 standard within the range of fine constraints [21]. The sand used had a specific gravity of 2.68, an absorption capacity of 2.88, and the material finer than sieve No. 200 was 80%.

2.4 Volcanic pumice (VP)

VP was utilized as an alternative aggregate to gravel in LWC mixtures which collected from Hatay region in Turkey. It has a light gray color, as shown in Figure 1.

Table 4: Sieve analysis of fine aggregate used and specification of BS [21]

Sieve size (mm)	Passing (%)	BS [21]			
		Limits	Fine	Medium	Coarse
4.75	100	89–100	—	—	—
2.36	89.0	60–100	80–100	65–100	60–100
1.18	74.5	30–100	70–100	45–100	30–90
0.60	55.5	15–100	55–100	35–80	15–45
0.30	21.5	5–70	5–70	5–48	5–40
0.015	3.5	0–15	—	—	—

Figure 1: The used VP.

Table 5: The chemical composition of VP

Oxide	Weight (%)
Cao	14.1
SiO_2	49.5
$Al2O_3$	16.4
Fe_2O_3	14.7
MgO	1.9
SO_3	0.2
K_2O	1.3
Na_2O	0.1

The utilized VP has a low density of 835 kg/m^3, allowing it to float on water. The chemical composition of the VC showed in Table 5.

2.5 Silica fume

The silica fume that used in this study was SikaFume-HR brand, provided from Beirut-Lebanon, which manufactures with a fineness of 0.1 µm. Table 6 shows the technical data of SikaFume-HR that provided from the production factory. In this study, silica fume has used in concrete mixes to increase the strength through the pozzolanic reaction with $Ca(OH)_2$ crystals for strengthening the bond between the cement paste and the aggregate surface at the transition zone.

2.6 Chemical admixtures

A super plasticizer (Sika ViscoCrete-SF 18) was used as a high-range water purifier, minimizing admixture and viscosity-modifying agent. The used proportion was 1% as weight % of cement. Table 7 shows the characteristics of the used super plasticizer as provided by the manufacturer.

Table 7: The characteristics of super-plasticizer used

Property	Sika ViscoCrete-SF 18
Chemical base	Modified poly carboxylates based polymer
Appearance/color	Light brownish liquid
pH value	3–7
Density	1.1 g/cm^3 ± 0.02 (at +20°C)
Dosage	1.0–2.0% by weight of cement

2.7 Water

All concrete mixes and samples curing processes were carried out in this article using normal tap water without any additions or treatments.

2.8 Fibers

In this study, two types of fibers were used, PPF (with crimped shape) and GF; the details are presented in Table 8 and Figure 2. Using fibers in concrete exposed many advantages, such as easy processing, low specific gravity, almost zero water adsorption, good chemical resistance, wide availability, and low cost.

2.9 Mixing and preparing specimens

All batches of concrete were mixed using a drum mixer with a capacity of 0.071 m^3. Each batch was used to cast six 100 mm × 100 mm × 100 mm cube specimens, six 100 mm × 200 mm cylinder specimens, and four 100 mm × 100 mm × 400 mm prism specimens for compressive strength, splitting tensile strength, and flexural strength testing, respectively, in iron molds. All molds were cleaned and the internal surfaces were lubricated before using.

Table 9 summarizes the proportion of mixes, where the normal reference concrete mix (M0), produced following the American Concrete Institute's mix design

Table 6: Technical data of SikaFume-HR

Property	Result
Composition	A latently hydraulic blend of active ingredient
Appearance	Grey powder
Dry bulk density	0.05–0.1 kg
Dosage	2–10% by weight of cement

Table 8: Details of GF and PPF

Type of fiber	Glass	Polypropylene
Length (mm)	12	25
Diameter (mm)	0.014	1.0
Aspect ratio	857.1	25
Density (kg/m^3)	2,600	910

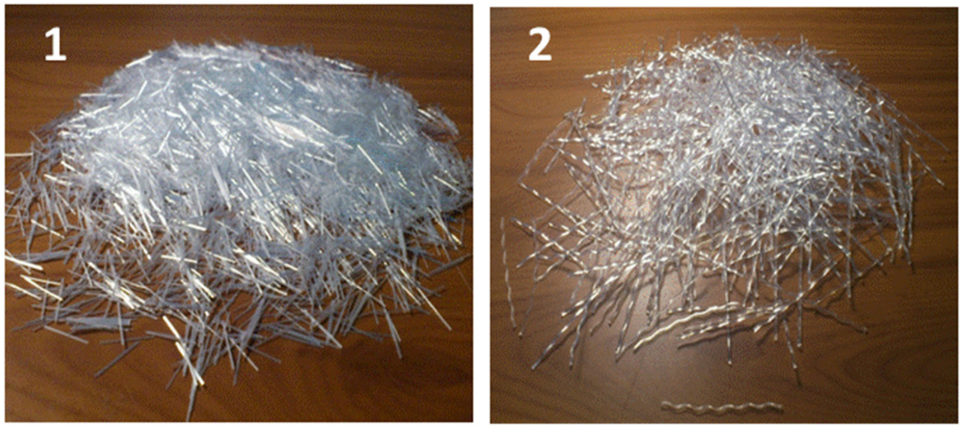

Figure 2: Fibers used in this study: (1) GF and (2) PPF.

Table 9: Mix Proportion of reference concrete and LWC mixes

Mix no.	Fibers (%)		Water (kg/m^3)	Cement (kg/m^3)	Sand (kg/m^3)	Coarse aggregate	VP (kg/m^3)
	GF	PPF					
M0	—	—	200	400	745.6	1344.4	0
M1	0.1	—	200	400	745.6	806.6	537.7
M2	0.3	—	200	400	745.6	806.6	537.7
M3	0.5	—	200	400	745.6	806.6	537.7
M4	0.7	—	200	400	745.6	806.6	537.7
M5	—	0.25	200	400	745.6	806.6	537.7
M6	—	0.5	200	400	745.6	806.6	537.7
M7	—	0.75	200	400	745.6	806.6	537.7
M8	—	1.0	200	400	745.6	806.6	537.7
M9	0.3	0.5	200	400	745.6	806.6	537.7
M10	0.5	0.5	200	400	745.6	806.6	537.7
M11	0.3	1	200	400	745.6	806.6	537.7
M12	0.5	1	200	400	745.6	806.6	537.7

standards [22], to achieve (C25) concrete mix with (w/c) equal to 0.5, super plasticizer was used in 1% as wt% of cement and the mix proportion of cement: sand: gravel was 1:1.86:3.36, whereas, LWC mixes (M1 to M12) produced by replacing 40% of the volume of coarse aggregate with volcanic pumice VP, with different proportions of fibers (singular and hybrid) as shown in Table 9.

Moreover, another thirteen high strength concrete mixes were prepared (M13 to M25), as shown in Table 10. Where, (M13) represents the high-strength concrete reference mix, w/c ratio was reduced to 0.3 with 1% super plasticizer and 10% of silica fume (as wt.% of cement) was used. In the same way, the HSC mixes (M14 to M25) were prepared by using different proportions of fibers (singular and hybrid) to study the influence of hybrid fibers on the mechanical properties of HSC mixes as shown in detail in Table 10.

3 Results and discussion

3.1 Compressive strength test results

Standard compressive cube tests using 100 mm × 100 mm × 100 mm samples were conducted to determine concrete compressive strength at 28-day age. The compressive strength of six samples were found of LWC and HSC, which presented in Figures 3 and 4, respectively. The effect of fiber type and content on compressive strength (as gaining or loosing % in strength) are presented in Tables 11 and 12. The results showed that, in general, increase the fiber content exposed increasing in compressive strength in both LWC and HSC mixes, similar results obtained by others [8,9,11]. Moreover, for the same fiber proportion (0.5%), using the glass fibers displayed

Table 10: Mix proportion of HSC mixes

Mix no.	Fibers (%)		Water (kg/m³)	Cement (kg/m³)	Sand (kg/m³)	Coarse aggregate (kg/m³)	Silica fume (kg/m³)
	GF	PPF					
M13	—	—	120	400	745.6	1344.4	40
M14	0.1	—	120	400	745.6	1344.4	40
M15	0.3	—	120	400	745.6	1344.4	40
M16	0.5	—	120	400	745.6	1344.4	40
M17	0.7	—	120	400	745.6	1344.4	40
M18	—	0.25	120	400	745.6	1344.4	40
M19	—	0.5	120	400	745.6	1344.4	40
M20	—	0.75	120	400	745.6	1344.4	40
M21	—	1.0	120	400	745.6	1344.4	40
M22	0.3	0.5	120	400	745.6	1344.4	40
M23	0.5	0.5	120	400	745.6	1344.4	40
M24	0.3	1	120	400	745.6	1344.4	40
M25	0.5	1	120	400	745.6	1344.4	40

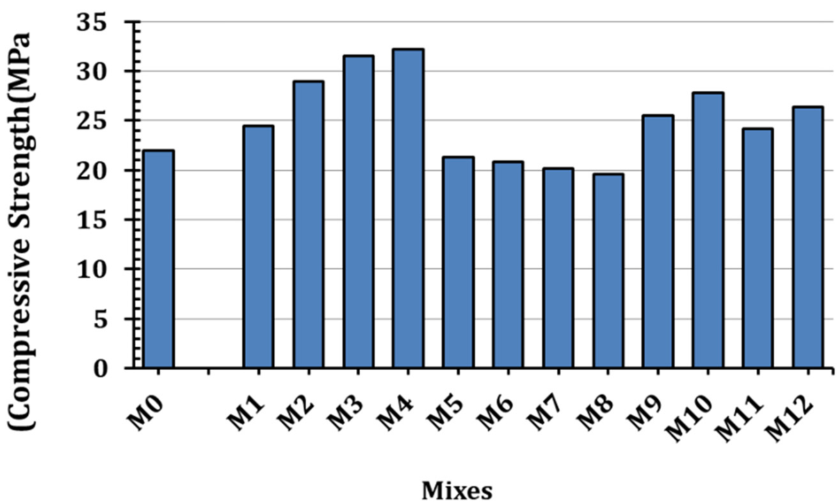

Figure 3: 28-Day compressive strength test results of LWC mixes.

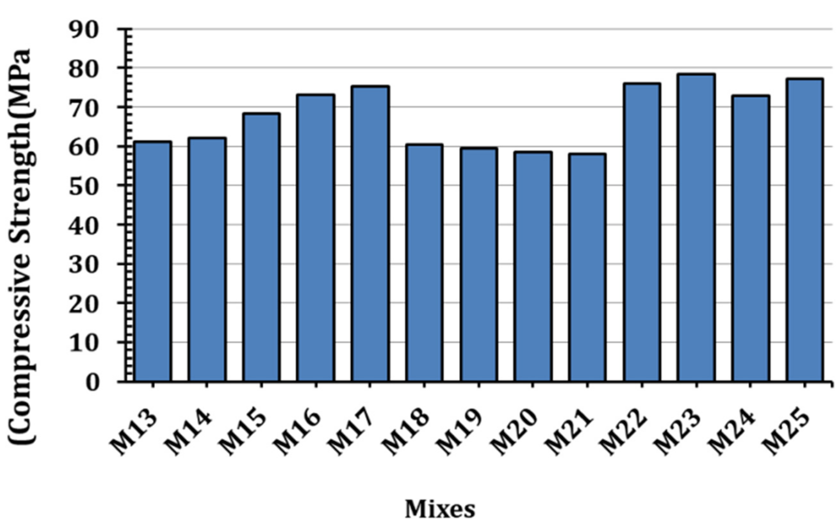

Figure 4: 28-Day compressive strength test results of HSC mixes.

Table 11: Compressive strength test results of LWC mixes

Mix no.	Fibers (%)		28-Day compressive strength (MPa)	Gaining (+) or losing (–) % in compressive strength
	GF	PPF		
M0	—	—	22.00	—
M1	0.1	—	24.50	+11.4
M2	0.3	—	29.00	+31.8
M3	0.5	—	31.50	+43.2
M4	0.7	—	32.20	+46.4
M5	—	0.25	21.35	−3.0
M6	—	0.50	20.80	−5.0
M7	—	0.75	20.20	−8.0
M8	—	1.00	19.60	−10.0
M9	0.3	0.5	25.52	+16.0
M10	0.5	0.5	27.82	+26.4
M11	0.3	1.0	24.20	+10.0
M12	0.5	1.0	26.40	+20.0

Table 12: Compressive strength test results of HSC mixes

Mix no.	Fibers (%)		28-Day compressive strength (MPa)	Gaining (+) or losing (–) % in compressive strength
	GF	PPF		
M13	—	—	61.20	—
M14	0.1	—	62.10	+1.50
M15	0.3	—	68.30	+11.60
M16	0.5	—	73.20	+19.60
M17	0.7	—	75.30	+23.00
M18	—	0.25	60.35	−1.00
M19	—	0.50	59.34	−3.00
M20	—	0.75	58.43	−4.00
M21	—	1.0	57.95	−5.00
M22	0.3	0.5	76.10	+24.30
M23	0.5	0.5	78.45	+28.20
M24	0.3	1.0	73.00	+19.28
M25	0.5	1.0	77.25	+26.22

growing in compressive strength up to 43% in LWC and 19.6% in HSC (mixes M3 in Table 11 and M16 in Table 12) in comparison with polypropylene fibers in the same proportion (0.5%), which displayed a reduction in strength of the LWC mixes up to −5% and in HSC mixes the reduction was −3%, (mixes M3 in Table 11 and M16 in Table 12) in comparison with polypropylene fibers at the same content (0.5%), which displayed a reduction in strength in LWC and HSC mixes within 5 and 3%, respectively (mixes M6 in Table 11 and M19 in Table 12). That could be related to the higher aspect ratio (length/ diameter ratio) of GF which equal to 857.1 in comparison with 25 for polypropylene fibers and that extremely improved the mechanical properties of glass fibers. Furthermore, dropping in strength of LWC and HSC mixes, that contain PPF, could be also related to the low stiffness and low ductility of PPF which affected negatively on strength. Similar results obtained by others [23,24].

The results displayed clearly that the optimal content of hybrid fibers as a combination was 0.5% GF + 0.5% PPF, and other proportion contents (mixes M22, M24, and M25) have not shown an effectiveness to use the content of these high fibers in comparison with the efficiency of using only GF with lower total fiber content (mix M7).

Adding GF to either LWC or HSC control mixes or that already have PPF caused strength improvement. On the contrary, adding PPF to the mixes that containing GF caused reduction in strength in LWC and HSC mixes (Tables 11 and 12). That could be correlated with the low elastic modulus of the PPF in comparison with the GF which has high elastic modulus, in addition to the higher aspect ratio (length/diameter ratio) of GF comparing with PPF as mentioned before.

Fibers also affect the followability and workability and reduce the backing density, which increases the internal defects' concrete. Moreover, mixing of long size fibers (PPF) with other in short size (GF) cannot give accurately prediction effect on the mechanical properties of concrete because fiber dispersion and fiber orientation also affect the compressive strength of concrete [25].

3.2 Splitting tensile strength test results

The splitting tensile strength test results of LWC and HSC mixes reinforced with glass, polypropylene, and hybrid fibers are shown in Tables 13 and 14, respectively.

In LWC mixes, increasing the GF contents caused increasing in splitting tensile strength values. Where, the highest splitting tensile strength value obtained with a maximum volume fraction of GF equal to (0.7%) (mix M4 in Table 13). This increment could be related to the high tensile strength of the GF, which bridge and arrested the cracks that initiated in the matrix consequently enhance the splitting tensile strength of LWC mixes, similar results were obtained by others [24,26].

Moreover, the LWC mixes reinforced with the PPF, the optimal content of PPF was 0.75% which gave the highest splitting tensile strength equal to 2.5 MPa (mix M7 in Table 13). While, the HSC mixes reinforced with the PPF, the optimal content of PPF was 1%, which gave the highest splitting tensile strength equal to 6.1 MPa (Mix M21 in Table 14). The optimal content of hybrid fibers was

Table 13: Splitting tensile strength test results of LWC mixes

Mix no.	Fibers (%)		28-Day splitting tensile strength (MPa)	Increasing % in splitting tensile strength
	GF	PPF		
M0	—	—	2.1	—
M1	0.1	—	2.3	9.0
M2	0.3	—	2.6	23.8
M3	0.5	—	2.9	36.7
M4	0.7	—	3.1	47.6
M5	—	0.25	2.3	9.0
M6	—	0.50	2.4	14.3
M7	—	0.75	2.5	18.0
M8	—	1.0	2.4	12.4
M9	0.3	0.5	2.7	26.6
M10	0.5	0.5	2.9	36.7
M11	0.3	1.0	2.5	20.9
M12	0.5	1.0	2.7	26.2

Table 14: Splitting tensile strength results of HSC mixes

Mix no.	Fibers (%)		28-Day splitting tensile strength (MPa)	Increasing % in splitting tensile strength
	GF	PPF		
M13	—	—	5.2	—
M14	0.1	—	5.4	2.8
M15	0.3	—	5.8	11.5
M16	0.5	—	6.0	15.6
M17	0.7	—	6.3	21.2
M18	—	0.25	5.4	3.8
M19	—	0.50	5.5	5.8
M20	—	0.75	5.9	12.5
M21	—	1.0	6.1	17.3
M22	0.3	0.5	5.9	13.3
M23	0.5	0.5	6.2	18.7
M24	0.3	1.0	5.9	14.4
M25	0.5	1.0	5.8	11.1

(0.5% GF + 0.5% PPF) that recorded the highest tensile strength in LWC and HSC mixes (Mixes M10 and M23 in Tables 13 and 14, respectively).

3.3 Flexural strength (modulus of rupture) test results

The flexural strength measured values at 28-day age are given in Tables 15 and 16 for all concrete mixes. The 28-day flexural strengths ranged from 3.6 to 4.5 MPa for LWC mixes, (Table 15) and from 12.1 to 14.35 MPa for HSC mixes (Table 16).

Table 15: Flexural strength test results of LWC mixes

Mix no.	Fibers (%)		28-Day flexural strength (MPa)	Increasing % in flexural strength
	GF	PPF		
M0	—	—	3.60	—
M1	0.1	—	3.82	6.10
M2	0.3	—	3.95	9.70
M3	0.5	—	4.30	19.40
M4	0.7	—	4.50	25.00
M5	—	0.25	3.62	0.50
M6	—	0.5	3.68	2.20
M7	—	0.75	3.80	5.50
M8	—	1.0	3.67	1.90
M9	0.3	0.5	3.99	9.16
M10	0.5	0.5	4.20	16.6
M11	0.3	1	3.89	8.00
M12	0.5	1	4.10	13.8

Table 16: Flexural strength test results of HSC mixes

Mix no.	Fibers (%)		Flexural strength at age 28 days (MPa)	Increasing % in flexural strength
	GF	PPF		
M13	—	—	12.1	—
M14	0.1	—	12.4	2.50
M15	0.3	—	12.9	6.60
M16	0.5	—	13.2	9.00
M17	0.7	—	13.3	9.90
M18	—	0.25	12.4	2.50
M19	—	0.5	12.9	6.60
M20	—	0.75	13.2	9.00
M21	—	1.0	13.6	11.57
M22	0.3	0.5	13.7	13.20
M23	0.5	0.5	14.35	18.60
M24	0.3	1	13.84	14.3
M25	0.5	1	13.44	2.8

The results display that using fiber reinforcement is very useful to boost the flexural strength of both LWC and HSC mixes. The optimal flexural strength increments of LWC were 25, 5.5, and 16.6% due to the inclusion of 0.7% GF, 0.75% PPF, and the combination of 0.5 GF + 0.5% PPF, respectively. Likewise, the optimal fibers content that gave the highest flexural strength values were 0.7% GF, 1% PPF and (0.5%GF + 0.5% PPF) for hybrid fibers in both LWC in Table 15, and HSC mixes in Table 16. The hypothesis behind that related to arresting the early tensile cracks in concrete by fibers which resulting in high tensile and flexural strength [27]. Using the GF in concrete mixes displayed greater enhancement in compressive, tensile and flexural strength comparing with PPF, this might be ascribed to enhanced bonding of GF with binder matrix.

4 Conclusions

According to test results of this investigation, the following conclusions can be drawn:

1. Increasing the GF content exposed increasing in compressive strength in both FRC, LWC and HSC.
2. Increasing fiber contents in LWC and HSC mixes reinforced with GF or PPF, displayed increasing in splitting tensile strength values.
3. Using 0.7% GF in LWC and HSC increased the compressive strength up to 46 and 23%, respectively.
4. Using PPF caused reduction in compressive strength of both, LWC and HSC within 5 and 3%, respectively.
5. Using 0.7% GF increased the splitting tensile strength of LWC and HSC up to 47.62 and 21.1%, respectively, and increased the flexural strength of the LWC mix by 25%.
6. The hybrid fibers with the content of 0.5% GF + 0.5% PPF were the best hybrid proportion and affected positively on the splitting tensile strength of LWC and HSC up to 36.67 and 18.65%, respectively.

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References

[1] Annamaneni KK, Dobariya BV, Krasnikovs A. Concrete, reinforced by carbon fibre composite structure, load bearing capacity during cracking. Environ Technol Resour Proc Int Sci Pract Conf. 2021;2:232–7.
[2] Xiao SH, Lin JX, Li LJ, Guo YC, Zeng JJ, Xie ZH, et al. Experimental study on flexural behavior of concrete beam reinforced with GFRP and steel-fiber composite bars. J Build Eng. 2021;43:103087.
[3] Ge W, Song W, Ashour AF, Lu W, Cao D. Flexural performance of FRP/steel hybrid reinforced engineered cementitious composite beams. J Build Eng. 2020;31:101329.
[4] Khabaz A. Performance evaluation of corrugated steel fiber in cementitious matrix. Constr Build Mater. 2016;128:373–83.
[5] Sikarskas D, Antonovič V, Malaiškiene J, Boris R, Stonys R, Šahmenko G. Modification of the Structure and Properties of Lightweight Cement Composite with PVA Fibers. Materials. 2021;14:5983.
[6] ACI Committee 544, State-of-The-Art Report on Fiber Reinforced Concrete, ACI 544 1R-96. Farmington Hills (MI); ACI Committee; 2022.
[7] Murthy Y, Sharda AI, Jain G. Performance of Glass Fiber Reinforced Concrete. Int J Eng Innovative Technol. 2012;1:246–8.
[8] Sangeetha P, Sumathi R. Behaviour of glass fiber wrapped concrete columns under uniaxial compression. Int J Adv Eng Technol. 2010;I:74–83.
[9] Kumar VS, Thomas BS and Christopher A. An Experimental Study on the Properties of Glass Fibre Reinforced Geopolymer Concrete. Int J Eng Res Appl. 2012;2:722–6.
[10] Fauzan RK, Fitrah ON, Lovina CAN, Al Jauhari Z. Experimental study on the effect of steel fiber waste type on high strength concrete. GEOMATE J. 2019;16(58):14–9.
[11] Nair MJ, Varghese R. Influence of glass fiber and polypropylene fiber on M30 grade concrete and its durability study. Int J Innovative Res Sci Eng Technol. 2017;6(5).
[12] Torres-Ortega R, Edgar B, Candelaria T, Yineth G, Ibeth C. High-strength concrete with natural aggregates, silica fume, and polypropylene macrofibers. Cienc e Ingeniería Neogranadina. 2021;31(2):27–40.
[13] Mahdi ZR. Behavior of fiber reinforced high performance concrete columns [dissertation]. Baghdad: University of Technology; 2006.
[14] Eren YA. Determination of mechanical properties of hybrid fiber reinforced concrete [dissertation]. Ankara: Middle East Technical University; 2004.

[15] Bentur A, Mindess S. Fiber reinforced cementitious composites. Kent: Elsevier Applied Science; 1990.
[16] Ramli M, Thanon E. Study the hybridization of different fibers on the mechanical properties of concrete: A mini review. Asian J Appl Sci. 2011;4(5):489–92.
[17] Banthia N, Gupta R. Hybrid fiber reinforced concrete (HyFRC): fiber synergy in high strength matrices. Mat Struct. 2004;37:707–16.
[18] Altun MG, Oltulu M. Effect of different types of fiber utilization on mechanical properties of recycled aggregate concrete containing silica fume. J Green Build. 2020;15(1):119–36.
[19] Tayeh BA, Agwa IS. Investigating the mechanical and microstructure properties of fibre-reinforced lightweight concrete under elevated temperatures. Case Stud Constr Mater. 2020;13:e00459.
[20] IQS No. 5. Standard Specifications for Portland Cement. Baghdad, Iraq: Iraqi Organization for Standards and Specifications; 1984.
[21] BS:882. Aggregates from Natural Source of Concrete. London, UK: British Standard Institution; 1992.
[22] ACI 211.1-91. Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass Concrete. Farmington Hills (MI), USA: ACI Committee; 1991.
[23] Banthia N, Sappakittipakorn M. Toughness enhancement in steel fiber reinforced concrete through fiber hybridization. Cem Concr Res. 2007;37(9):1366–72.
[24] Ali B, Qureshi LA. Influence of glass fibers on mechanical and durability performance of concrete with recycled aggregates. Constr Build Mater. 2019;228:116783.
[25] Kasagani H, Rao CBK. Effect of graded fibers on stress strain behaviour of glass fiber reinforced concrete in tension. Constr Build Mater. 2018;183:592–604.
[26] Moghadam A, Izadifard RA. Effects of steel and glass fibers on mechanical and durability properties of concrete exposed to high temperatures. Fire Saf J. 2020;113:102978.
[27] Teng S, Afroughsabet V, Ostertag, CP. Flexural behavior and durability properties of high performance hybrid-fiber-reinforced concrete. Constr Build Mater. 2018;182:504–15.