AUT Journal of Civil Engineering

AUT J. Civil Eng., 6(2) (2022) 319-336
DOI: 10.22060/ajce.2023.21616.5806

The Effect of GGBFS with Steel and Carbon Fibers on the Mechanical Properties and Durability of Concrete

S. M. Miralami[1], S. Hajati Ziabari[2], M.R. Esfahani[3*]

[1] Department of Civil Engineering, Rahman Institute of Higher Education, Ramsar, Iran.
[2] Department of Civil Engineering, Kadous Institute of Higher Education, Rasht, Iran.
[3] Department of Civil Engineering, Ferdowsi University of Mashhad, Mashhad, Iran.

ABSTRACT: The present study evaluates the effect of ground granulated blast furnace slag (GGBFS) with steel and carbon fibers on concrete's mechanical properties and durability. To this end, the effect of GGBFS at weight percentages of 30, 40, and 50%, steel fibers at 0.5, 1, and 1.5%, and carbon fibers at 0.2, 0.4, and 0.6% were assessed. Additionally, fresh and hardened concrete densities and fresh concrete slump values were determined. Compressive, splitting tensile, and flexural strengths, as well as an abrasion test (100, 200, and 300 cycles), were used to investigate the mechanical properties of concrete at 28 and 90 days of age. Furthermore, the water absorption percentage of the specimens was evaluated at 90 days. The results indicated that the maximum slump reduction was observed in the specimen with 50% GGBFS, along with 1.5% steel fiber and 0.6% carbon fiber. Specimens containing 50% GGBFS alternative, 1.5% steel fiber, and 0.4% carbon fiber had the highest compressive strength, splitting tensile strength, abrasion resistance, and lowest water absorption percentage. The optimum level of GGBFS, steel, and carbon fibers content in terms of compressive strength, splitting tensile strength, flexural strength, abrasion resistance, and water absorption were found to be 50, 1.5, and 0.4%, respectively. Also, the flexural strengths of the optimal mixing design were 5.62 and 6.12 MPa at the ages of 28 and 90 days, respectively. Moreover, scanning electron microscopy (SEM) was used to characterize the microstructure of concrete containing GGBFS. SEM images of the concrete containing GGBFS revealed dense microstructures.

Review History:

Received: Jul. 21. 21. 2022
Revised: Mar. 06. 2023
Accepted: Mar. 17. 2023
Available Online: Mar. 26. 2023

Keywords:

Ground granulated blast furnace slag (GGBFS)
Steel fibers
Carbon fibers
Mechanical properties
Durability

1- Introduction

The cement industry is one of the most polluting industries. The environmental issues concerning cement production include dust dispersion, respiratory diseases, air pollution, groundwater pollution, and vegetation loss. A proper alternative to solve these problems is ground-granulated blast furnace slag (GGBFS). Compared to cement, using GGBFS has the advantages of reduced cost of concrete production, reduced environmental pollution due to low carbon dioxide emission, and lower energy consumption required for its production. GGBFS is a by-product obtained in the production of pig iron in the blast furnace. This material can be an alternative to some cement used in concrete construction for the pozzolanic properties [1, 2]. Johari et al. [3] experimentally investigated the effect of GGBFS on the compressive strength of concrete specimens. They showed that an increase in the GGBFS replacement in the early ages of concrete reduced the compressive strength of specimens. Moreover, the highest compressive strength was obtained for a specimen containing 20% GGBFS at the age of 365 days. Boukendakdji et al. [4] studied the effect of GGBFS on the mechanical properties of self-compacting concrete. The ordinary Portland cement (OPC) was replaced with GGBFS at weight percentages of 0 to 25% with increments of 5%. The results showed that the efficiency of self-compacting concrete improved with the rise in the GGBFS. The effect of the GGBFS on the compressive strength of the concrete specimens in dry and humid conditions was investigated. GGBFS replacement was done at weight percentages of 20-80% with increments of 20%. The results demonstrated that by increasing the weight percentage of GGBFS, the compressive strength of concrete specimens under dry curing conditions decreased [5]. Gholampour and Ozbakkaloglu [6] investigated the effect of GGBFS replacement with weight percentages of 50 to 90% on the performance and mechanical properties of concrete. The results showed that increasing the weight percentage of the GGBFS could reduce the slump of concrete specimens by 51%. It also decreased the compressive strength of specimens in the early ages of the concrete. Berndt [7] found that replacing 50% of cement with GGBFS yielded the best results in increasing concrete specimens' compressive and splitting tensile strength. Wang and Lin [8] investigated the effect of GGBFS replacement by 0%, 15%, and 30% on the mechanical properties of self-compacting concrete. According to the results, the compressive strength of the specimen with 15% GGBFS was 13% higher than

*Corresponding author's email: Esfahani@um.ac.ir

Table 1. Physical properties of cement and GGBFS.

Type	Density (kg/m^3)	Specific surface area (cm^2/g)	Setting time (min)		Compressive strength (MPa)		
			Initial	Final	3 days	7 days	28 days
Cement	3140	2916	140	210	25	41	55
GGBFS	2890	3050	-	-	-	-	-

that of the control specimen. Ashish et al. [9] studied the effect of magnesium chloride and magnesium sulfate on the compressive strength and durability of concrete containing GGBFS. The results indicated an increase in the durability of concrete containing 20% GGBFS. The use of 40 and 60% GGBFS slightly reduced the concrete durability. Moreover, the compressive strength of specimens containing 20% GGBFS increased significantly. The effect of the GGBFS and fly ash (FA) with steel and polypropylene (PP) fibers on the mechanical properties of high-performance concrete (HPC) after exposure to different temperatures was investigated. The results showed that using GGBFS and FA with the hybrid of steel and PP fibers can significantly improve the mechanical properties of HPC concrete [10]. By increasing the bearing capacity, toughness, abrasion resistance, and crack resistance, steel fibers play a significant role in increasing usability and thus reducing the maintenance costs of structures. The common problems of such fibers are corrosion and high density, which increase the weight of structures. Compared to steel fibers, carbon fibers have a higher elastic modulus and a lower density. Therefore, using carbon fibers to increase durability and reduce density can have a significant effect on fiber-reinforced concrete results. The advantages of carbon fibers include high thermal resistance, corrosion resistance, the capability of being mixed with high volume percent with concrete, and chemical stability in aggressive environments [11-13]. Studies on using carbon fibers reveal a significant rise in tensile strength, flexural strength, compressive strength, and toughness of concrete [14-16]. Cucchiara et al. [17] evaluated the effectiveness of steel fibers in compressive and splitting tensile strength of concrete specimens. The results showed that using steel fibers with volume percentages of 1 and 2% significantly increased the compressive and splitting tensile strength of the specimens. In an experimental study, the hybrid effect of steel fibers and GGBFS was investigated on the mechanical properties of concrete. It was found that the rise in the volume percentage of GGBFS replacement by up to 60% raised the compressive strength of the specimens at the age of 28 days. Furthermore, the highest compressive and splitting tensile strengths of specimens were obtained using 20% GGBFS with 0.6% steel fibers [18]. The effect of carbon fibers at volume percentages of 0 to 2% with increments of 0.5% was evaluated on the efficiency and mechanical properties of concrete. It was found that the addition of carbon fibers significantly reduced the performance of concrete while increasing the compressive, splitting tensile, and flexural strengths [19].

Limited studies have been performed on the performance of GGBFS concrete containing steel and carbon fibers. The information about the effect of GGBFS with steel and carbon fibers on the abrasion resistance of concrete is very limited. Therefore, the performance of concrete containing GGBFS needs further investigation, especially regarding the mechanical properties and durability when steel and carbon fibers are added to the concrete mix. The main objective of the research described in this paper is to investigate the mechanical properties and durability of concretes containing GGBFS with steel and carbon fibers. This study is also the first to investigate the compressive strength, splitting tensile strength, flexural strength, abrasion resistance, and water absorption of concrete containing the combination of GGBFS with steel and carbon fibers. The paper initially provides a summary of the experimental program, including material properties, specimen productions, and testing procedures, which is followed by the results of the experimental program. A detailed discussion of the results is subsequently presented to discuss the effects of GGBFS at weight percentages of 30, 40, and 50%, steel fibers at 0.5, 1, and 1.5%, and carbon fibers at 0.2, 0.4, and 0.6%. The technology presented in this study is a promising solution to improve the environmental impact of both industrial by-products and concrete.

The fresh properties of concrete, including slump, fresh and hardened density were tested.

2- Experimental Program

2- 1- Materials

Tables 1 and 2 represent the physical and chemical analysis of the consumed types of cement and GGBFS in this research, respectively. ASTM C150 [20] standard was used to determine the physical and chemical properties of Portland cement type 2 produced in Abyek- Qazvin (Iran) Cement Company. Fig. 1(a) shows the GGBFS used in this research. In this research, the GGBFS was prepared by Bana Bonyan Zist Fanavar Company. To increase the concrete capability, a superplasticizer with a density of 1.03 kg/l and a pH=7 was used. ASTM C494 [21] standard was used for superplasticizer chemical analysis. The maximum size of coarse aggregate was 12 mm, and the maximum size of fine aggregate was 5 mm. Fig. 2 shows the particle grading of the aggregates. The properties of aggregates and the characteristics of steel and carbon fibers are respectively presented in Tables 3 and 4. Figs. 1(b) and 1(c) show the used steel and carbon fibers.

Table 2. Chemical composition of cement and GGBFS (%).

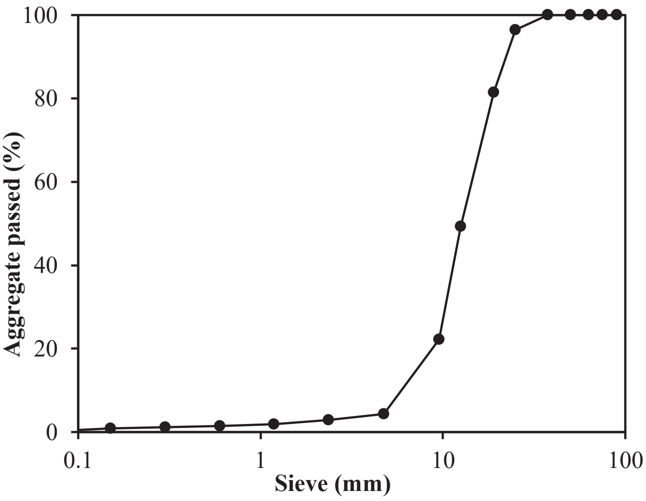
Component	Portland Cement	GGBFS
CaO	62.28	38.46
Na_2O	0.30	0.3
K_2O	0.75	0.75
MgO	3.22	10
SO_3	1.89	0.1
Fe_2O_3	3.86	0.51
Al_2O_3	4.76	13.47
SiO_2	20.28	35.08
Cl	0.02	-

(a) Sample of GGBFS

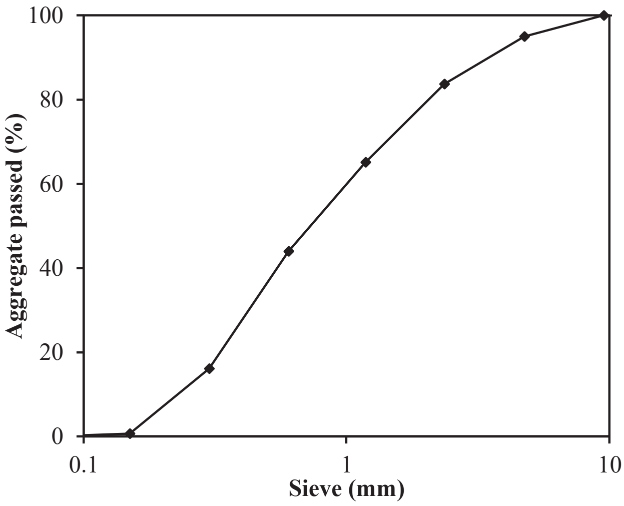
(b) Hooked-end steel fibers

(c) Carbon fibers

Fig. 1. GGBFS and fibers used in this study.



(a)



(b)

Fig. 2. Grain size distribution curve of (a) Coarse aggregates and (b) Fine aggregates.

Table 3. Properties of natural aggregates.

Aggregate type	Size (mm)	Density (kg/m^3)	Water absorption (%)	
			1 hr	24 hr
Coarse aggregate	9.50-37.50	2550	1.43	3.90
Sand	0.15-4.75	2600	1.75	4.30

Table 4. Characteristics of steel and carbon fibers.

Fiber type	Steel	Carbon
Density (kg/m^3)	7850	1600
Length (mm)	50	6.4
Equivalent diameter (mm)	1	0.001
Tensile strength (MPa)	1050	3800
Modulus of elasticity (MPa)	200	230

2- 2- Mixture proportions and production

Table 5 lists the mixed designs of specimens. ACI 211.1 [22] standard was used to determine the concrete mixture proportions. Based on this regulation, the concrete of the reference specimen was designed to give a slump value of 80 ± 2 mm, which was achieved by using varying amounts of superplasticizer. In this research, 25 mix designs were determined, using which 256 specimens were made and tested. To prepare the samples, at first, sand, coarse aggregates, cement, GGBFS, and (carbon or steel) fibers were mixed in the dry mode for one minute. Then, half of the water was added, and the materials were mixed again. The second half of the water was added with a superplasticizer and mixed for two more minutes. In all specimens, the water/cement ratio was constant, equal to 0.4. After 24 hours, the specimens were removed from the molds and stored in humid conditions at 23±2°C until testing. Symbol W denotes a specimen without GGBFS and fibers (control specimen). Symbols GaCbSc, GaCb, and GaSb represent samples with GGBFS and (carbon and steel) fibers, samples with GGBFS and carbon fibers, and samples with GGBFS and steel fibers, respectively. G represents the GGBFS replacement, and C and S show carbon and steel fibers, respectively. Moreover, symbols a, b, and c denote the weight percentages of GGBFS replacement (30, 40, and 50%), carbon fibers (0.2, 0.4, and 0.6%), and steel fibers (0.5, 1, and 1.5%), respectively.

The specimens were divided into groups with similar symbols to compare the results. Accordingly, the first group shows the control specimen, and the second group with three sub-groups represents the various weight percentage of GGBFS. Each of the third to fifth groups consists of three subgroups, in each of which the weight percentages of GGBFS replacement were examined by keeping the weight percentage of steel fibers constant. Moreover, the weight percentages of GGBFS were also evaluated in three sub-groups by assuming the weight percentage of the carbon fibers constant in each of the sixth to eighth groups. The ninth to eleventh groups show the effect of the combination of steel and carbon fibers with a GGBFS replacement percentage of 50% (the optimum value). Cubic specimens with dimensions 150×150×150 mm3 were made to measure their compressive strength according to BS EN 12390-3 [23]. Cylindrical specimens with a diameter of 150 mm and a length of 300 mm were also created to perform the splitting tensile strength tests according to ASTM C496 [24]. A three-point bending test was also used to obtain the specimens' flexural strength. To this end, prismatic specimens with a cross-section of 100×100 mm2 and a length of 700 mm were made according to ASTM C1609 [25], in which the distance between the supports and the distance between the loading points are recommended to be 300 and 100 mm, respectively. In this research, the method suggested in BS EN 1338 [26] was used to perform the abrasion test, which requires a circular steel plate with a diameter of 200 mm, a thickness of 70 mm, and a speed of 75 cycles/min. The abrasive powder was spread through a funnel on the grinding path, and Al2O3 was used as the abrasive dust as recommended by the code. By adjusting the outlet nozzle of the device, it could spread 0.5 ± 3.5 L/min of abrasive powder on the abrasive surface. The abrasion test specimens were 100 ×100×150 mm3 prisms. The groove length was measured for 100, 200, and 300 cycles. Then, the abrasion tests were performed on both the left and right sides of the specimens while recording the average value measured for each specimen. It should be noted that the compressive strength, splitting tensile strength, flexural strength, and abrasion tests were performed at 28- and 90-day ages. Cubic specimens with dimensions 100×100×100 mm3 were made to study the water absorption percentage at the age of 90 days according to the ASTM C642 [27]. As the specimens reached the age of 90 days, they were extracted from the curing pond, placed in an oven for 24 h, and weighed. The weight of the saturation state was also measured after 24 hours of immersion in water.

Table 5. Mix proportions of concrete (kg/m³).

Group	Mix ID	PC*	Water	Sand	Coarse aggregate	SP**	Steel fiber	Carbon fiber	GGBFS***
1	W	400	160	736	1104	2.000	0	0	0
2	G30	280	160	736	1104	2.000	0	0	120
	G40	240	160	736	1104	2.000	0	0	160
	G50	200	160	736	1104	2.000	0	0	200
3	G30C0S0.5	280	160	736	1104	2.008	2	0	120
	G40C0S0.5	240	160	736	1104	2.006	2	0	160
	G50C0S0.5	200	160	736	1104	2.008	2	0	200
4	G30C0S1	280	160	736	1104	2.115	4	0	120
	G40C0S1	240	160	736	1104	2.119	4	0	160
	G50C0S1	200	160	736	1104	2.118	4	0	200
5	G30C0S1.5	280	160	736	1104	2.123	6	0	120
	G40C0S1.5	240	160	736	1104	2.125	6	0	160
	G50C0S1.5	200	160	736	1104	2.121	6	0	200
6	G30C0.2S0	280	160	736	1104	2.005	0	0.8	120
	G40C0.2S0	240	160	736	1104	2.003	0	0.8	160
	G50C0.2S0	200	160	736	1104	2.004	0	0.8	200
7	G30C0.4S0	280	160	736	1104	2.005	0	1.6	120
	G40C0.4S0	240	160	736	1104	2.005	0	1.6	160
	G50C0.4S0	200	160	736	1104	2.004	0	1.6	200
8	G30C0.6S0	280	160	736	1104	2.005	0	2.4	120
	G40C0.6S0	240	160	736	1104	2.004	0	2.4	160
	G50C0.6S0	200	160	736	1104	2.006	0	2.4	200
9	G50C0.2S0.5	200	160	736	1104	2.110	2	0.8	200
	G50C0.2S1	200	160	736	1104	2.116	4	0.8	200
	G50C0.2S1.5	200	160	736	1104	2.156	6	0.8	200
10	G50C0.4S0.5	200	160	736	1104	2.115	2	1.6	200
	G50C0.4S1	200	160	736	1104	2.119	4	1.6	200
	G50C0.4S1.5	200	160	736	1104	2.119	6	1.6	200
11	G50C0.6S0.5	200	160	736	1104	2.128	2	2.4	200
	G50C0.6S1	200	160	736	1104	2.123	4	2.4	200
	G50C0.6S1.5	200	160	736	1104	2.130	6	2.4	200

*PC: Portland Cement; **SP: Superplasticizer; ***GGBFS: Ground Granulated Blast Furnace Slag

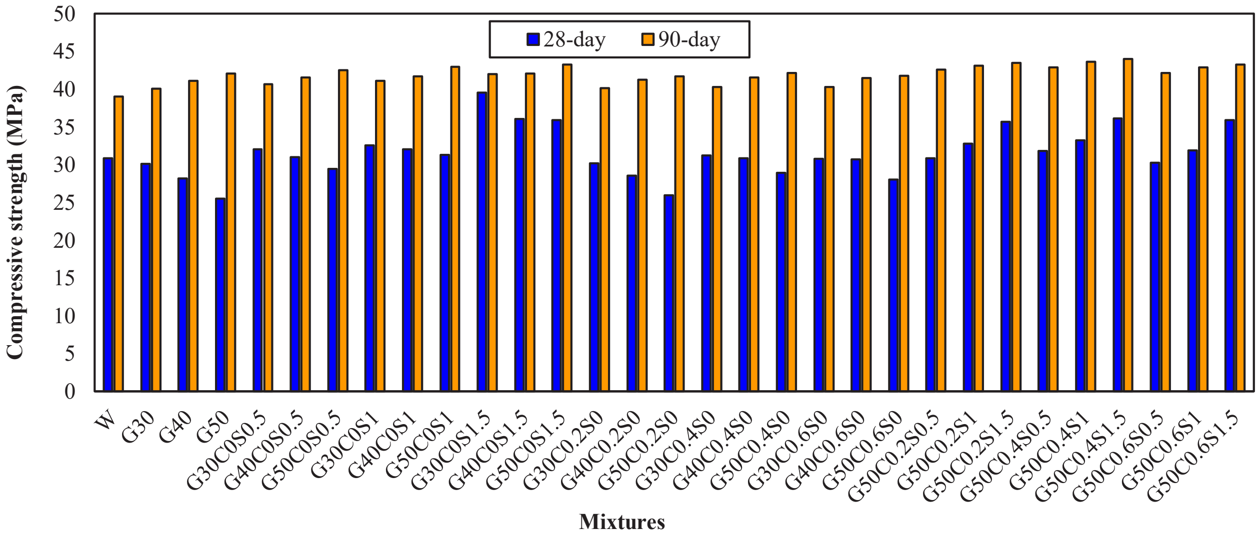


Fig. 3. Slump test results of concrete mixes.

3- Results and Discussion

3- 1- Workability of fresh concrete

Fig. 3 shows the slump test results of the specimens performed in accordance with the ASTM C143 [28]. The slump value of the control specimen was measured at 85 mm. By increasing the percentage of GGBFS, the slump of specimens in the second group decreased significantly. The reduction of the specimens' slump in this group can be justified by the lower capillary pore volume of the GGBFS compared to cement. Similar results have been reported in the literature [29, 30]. By comparing the slumps of specimens with steel fibers (groups 3, 4, 5) and carbon fibers (groups 6, 7, and 8), it was found that the presence of steel fibers had a significant effect on lowering the slump values. For example, the maximum slump reduction was observed in specimen G50C0S1.5 from group 5 with a value of 60 mm (29.41% compared to the control specimen) and specimens G50C0.4S0, G30C0.6S0, G40C0.6S0, and G50C0.6S0 from groups 7 and 8 with a value of 75 mm (11.77% compared to the control specimen). This can be attributed to the geometry of steel fibers compared to carbon fibers. Furthermore, using the combination of GGBFS, steel fibers, and carbon fibers resulted in a significant reduction in the slump of the specimens. In this regard, the maximum slump reduction was observed in specimen G50C0.6S1.5 from group 11 with a value of 55 mm (35.29% compared to the control specimen).

3- 2- Density of concrete

Table 6 lists the densities of the fresh and hardened specimens based on the ASTM C138 [31]. The density of the fresh concrete specimens varied from 2365 to 2407 kg/m^3. In the fresh state, with the GGBFS replacements of 30, 40, and 50% in group 2, the densities of the concrete specimens were 2381, 2379, and 2365 kg/m3 (reductions of 0.68, 0.75, and 1.34% compared to the control specimen), respectively. This is justifiable by comparing the densities of GGBFS (2890 kg/m^3 in this research) and cement (3140 kg/m^3 in this research). The addition of steel and carbon fibers increased the density of fresh concrete. At a constant weight percentage of the GGBFS, the densities of steel fiber specimens were much higher than those of the carbon fiber specimens, which can be attributed to the higher density of steel fibers (7850 kg/m^3 in this study) compared to the carbon fibers (1600 kg/m^3 in this study). The maximum density in the fresh state was recorded for specimen G30C0S1.5 (containing 30% GGBFS and 1.5% steel fibers) with a value of 2407 kg/m^3 (a reduction of 0.42% compared to the control specimen). Furthermore, the densities of the hardened concrete specimens varied between 2271 and 2369 kg/m^3. The densities of the concrete specimens in the hazrdened state with GGBFS replacements of 30, 40, and 50% in group 2 equaled 2300, 2299, and 2271 kg/m^3 with reductions of 0.17, 0.22, and 1.43% compared to the control specimen, respectively. The density of the hardened concrete in specimens with steel fibers (groups 3 to 5) and carbon fibers (groups 6 to 8) varied between 2369 kg/m^3 (an increase of 2.82% compared to the control specimen) and 2273 kg/m^3 (a reduction of 1.35% compared to the control specimen), respectively. Furthermore, the changes in the density of hardened concrete specimens with a combination of GGBFS, steel, and carbon fibers in groups.

Table 6. The density of specimens in the fresh and hardened states.

Group	Mix ID	Density (kg/m^3)	
		Fresh State	Hardened State
1	W	2397	2304
2	G30	2381	2300
	G40	2379	2299
	G50	2365	2271
3	G30C0S0.5	2385	2303
	G40C0S0.5	2379	2299
	G50C0S0.5	2371	2274
4	G30C0S1	2395	2326
	G40C0S1	2391	2308
	G50C0S1	2374	2298
5	G30C0S1.5	2407	2369
	G40C0S1.5	2400	2356
	G50C0S1.5	2393	2354
6	G30C0.2S0	2381	2301
	G40C0.2S0	2381	2299
	G50C0.2S0	2366	2273
7	G30C0.4S0	2382	2309
	G40C0.4S0	2381	2301
	G50C0.4S0	2367	2288
8	G30C0.6S0	2389	2319
	G40C0.6S0	2379	2317
	G50C0.6S0	2371	2295
9	G50C0.2S0.5	2373	2298
	G50C0.2S1	2375	2298
	G50C0.2S1.5	2395	2323
10	G50C0.4S0.5	2375	2297
	G50C0.4S1	2379	2301
	G50C0.4S1.5	2398	2339
11	G50C0.6S0.5	2379	2300
	G50C0.6S1	2381	2298
	G50C0.6S1.5	2401	2355

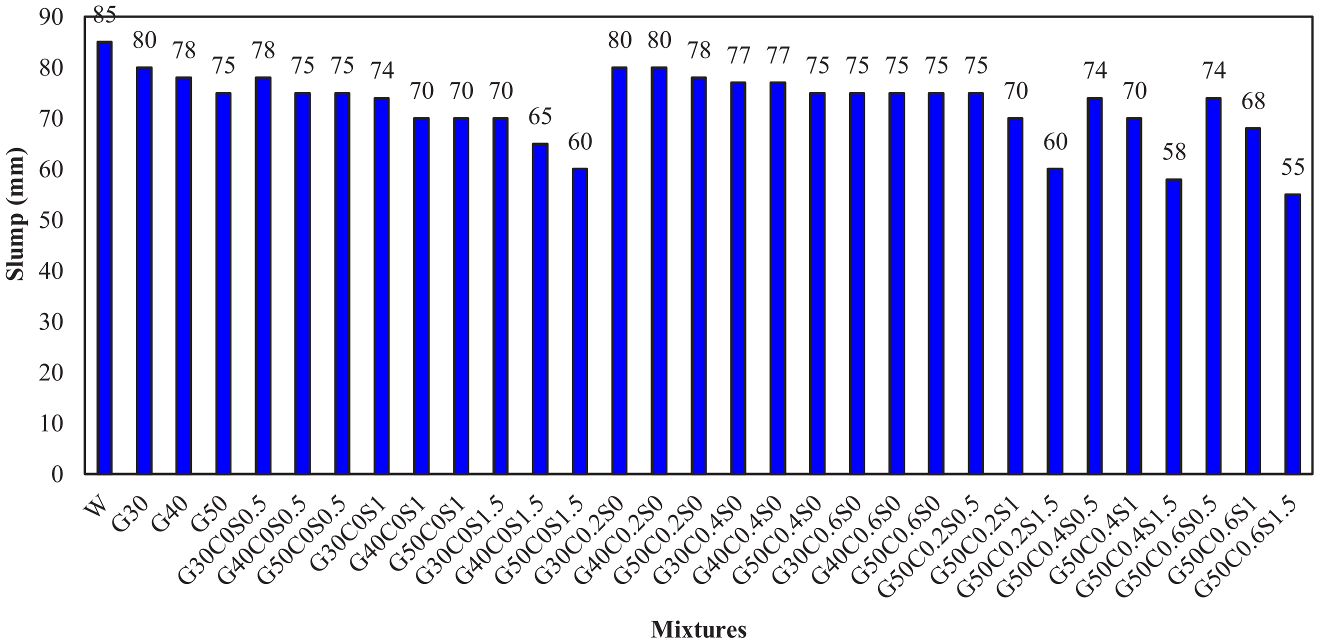


Fig. 4. The compressive strength of specimens at the age of 28 and 90 days.

3- 3- Mechanical properties of hardened concrete

3- 3- 1- Compressive strength

Fig. 4 shows the compressive strength of the specimens at the ages of 28 and 90 days. Table 7 presents the mean, standard deviation, and coefficient of variation of the compressive strength. Each mean value presents the average compressive strength of three tested specimens. As can be seen in the table, the standard deviations and coefficients of variation of specimens of groups 2 to 11 are not much different from those of the control specimen. According to Fig. 4, at 28 days of curing, the specimens with GGBFS replacement in group 2 had lower compressive strength than the control specimen. For instance, the compressive strength of specimens G30, G40, and G50 decreased by 2.59, 8.74, and 17.45%, respectively, compared to that of the control specimen. The rise in the age of the specimens from 28 to 90 days could raise the compressive strength of the specimens. At the age of 90 days, the compressive strength of specimens G30, G40, and G50 increased by 2.69, 5.69, and 7.84% compared to that of the control specimen. This might be due to the fact that by increasing the specimens' protection period to 90 days, the calcium hydroxide (CH) resulting from the hydrated cement reacts with the GGBFS to form secondary hydration that significantly increases the compressive strength of the specimens. The previous studies mainly showed that the compressive strength of specimens with GGBFS at the early ages of curing was inversely related to the amount of GGBFS [32-38].

According to the obtained compressive strengths for specimens of groups 3 to 5 (containing steel fibers), increasing the steel fibers from 0.5% to 1.5% significantly raised the compressive strength compared to the control specimen. The maximum value of this parameter in the specimen with 30% GGBFS and 1.5% steel fibers at the age of 28 days was 39.54 MPa (an increase of 28% compared to the control specimen). Meanwhile, the corresponding value was 43.24 MPa for the specimen with 50% GGBFS and 1.5% steel fibers at the age of 90 days (an increase of 10.84% compared to the control specimen). It should be noted that specimens with 0.4% carbon fibers (group 7) had a higher maximum compressive strength than groups 6 and 8 (specimens with 0.2 and 0.6% carbon fibers, respectively). In other words, the addition of 0.4% carbon fibers led to the optimum result. By comparing the compressive strengths of groups 3 to 5 and groups 6 to 8, it can be found that the compressive strengths of specimens with steel fibers were significantly higher than those of specimens with carbon fibers. The higher elastic modulus and hooked-end shape of steel fibers compared to carbon fibers restrict the propagation of cracks, change the orientation of cracks, and improve the compressive strength of specimens. It is worth noting that specimen G50C0.4S1.5 with 50% GGBFS, 0.4% carbon fibers, and 1.5% steel fibers had the maximum compressive strength, being equal to 36.12 and 43.98 MPa at the ages of 28 and 90 days (increased by 16.93 and 12.74% compared to the control specimen), respectively.

Table 7. Statistical parameters for the compressive strength.

Group	Mix ID	Statistical parameters					
		28-day			90-day		
		AVG*	SD**	COV (%) ***	AVG*	SD**	COV (%) ***
1	W	30.89	0.21	0.68	39.01	0.28	0.72
2	G30	30.09	0.25	0.83	40.06	0.29	0.72
	G40	28.19	0.29	1.03	41.08	0.33	0.80
	G50	25.50	0.31	1.22	42.07	0.33	0.78
3	G30C0S0.5	32.05	0.23	0.72	40.64	0.25	0.62
	G40C0S0.5	31.01	0.26	0.84	41.58	0.27	0.65
	G50C0S0.5	29.47	0.27	0.92	42.51	0.24	0.56
4	G30C0S1	32.57	0.25	0.77	41.08	0.31	0.75
	G40C0S1	32.04	0.23	0.72	41.71	0.22	0.53
	G50C0S1	31.29	0.25	0.80	42.98	0.25	0.58
5	G30C0S1.5	39.54	0.35	0.89	41.97	0.33	0.79
	G40C0S1.5	36.08	0.29	0.80	42.08	0.24	0.57
	G50C0S1.5	35.89	0.28	0.78	43.24	0.29	0.67
6	G30C0.2S0	30.16	0.29	0.96	40.12	0.35	0.87
	G40C0.2S0	28.54	0.25	0.88	41.23	0.32	0.78
	G50C0.2S0	25.92	0.29	1.12	41.68	0.34	0.82
7	G30C0.4S0	31.23	0.27	0.86	40.28	0.26	0.65
	G40C0.4S0	30.83	0.25	0.81	41.54	0.32	0.77
	G50C0.4S0	28.91	0.21	0.73	42.13	0.28	0.66
8	G30C0.6S0	30.79	0.25	0.81	40.25	0.29	0.72
	G40C0.6S0	30.74	0.32	1.04	41.44	0.33	0.80
	G50C0.6S0	28.00	0.31	1.11	41.74	0.35	0.84
9	G50C0.2S0.5	30.87	0.25	0.81	42.59	0.29	0.68
	G50C0.2S1	32.79	0.27	0.82	43.12	0.26	0.60
	G50C0.2S1.5	35.68	0.27	0.76	43.45	0.23	0.53
10	G50C0.4S0.5	31.81	0.28	0.88	42.88	0.31	0.72
	G50C0.4S1	33.25	0.26	0.78	43.61	0.18	0.41
	G50C0.4S1.5	36.12	0.19	0.53	43.98	0.35	0.80
11	G50C0.6S0.5	30.25	0.33	1.09	42.15	0.21	0.50
	G50C0.6S1	31.91	0.29	0.91	42.87	0.32	0.75
	G50C0.6S1.5	35.91	0.31	0.86	43.22	0.15	0.35

*AVG: Mean Values; **SD: Standard Deviation; ***COV: Coefficient of Variation

Table 8. The splitting tensile strength of specimens at the ages of 28 and 90 days.

Group	Mix ID	Splitting Tensile Strength (MPa)	
		28-day	90-day
1	W	3.22	3.82
2	G30	2.89	3.71
	G40	2.73	3.69
	G50	2.65	3.67
3	G30C0S0.5	2.94	3.98
	G40C0S0.5	2.81	3.84
	G50C0S0.5	2.75	3.79
4	G30C0S1	3.18	4.12
	G40C0S1	3.16	3.97
	G50C0S1	3.09	3.88
5	G30C0S1.5	3.94	4.51
	G40C0S1.5	3.86	4.48
	G50C0S1.5	3.79	4.23
6	G30C0.2S0	2.91	3.87
	G40C0.2S0	2.79	3.79
	G50C0.2S0	2.68	3.75
7	G30C0.4S0	2.95	4.01
	G40C0.4S0	2.83	3.88
	G50C0.4S0	2.79	3.81
8	G30C0.6S0	2.89	3.87
	G40C0.6S0	2.80	3.85
	G50C0.6S0	2.71	3.72
9	G50C0.2S0.5	2.78	3.83
	G50C0.2S1	3.11	3.91
	G50C0.2S1.5	3.79	4.25
10	G50C0.4S0.5	2.79	3.88
	G50C0.4S1	3.15	3.95
	G50C0.4S1.5	4.02	4.33
11	G50C0.6S0.5	2.75	3.81
	G50C0.6S1	3.12	3.92
	G50C0.6S1.5	3.82	4.22

3- 3- 2- Splitting tensile strength

Fig. 5 and Table 8 show the splitting tensile strengths of specimens at the ages of 28 and 90 days. According to the results, increasing the GGBFS from 30% to 50% reduced the splitting tensile strength of specimens of group 2 at the age of 28 days compared to the control specimen by 10.25, 15.22, and 17.70%, respectively. The reduction percentages in the splitting tensile strength of specimens with 30, 40, and 50% GGBFS at the age of 90 days were 2.88, 3.40, and 3.93% in comparison with the control specimen. Aghaeipour and Madhkhan [39] found similar results in this regard.

It seems that adding (steel or carbon) fibers to the specimens containing GGBFS significantly increases the splitting tensile strength compared to the control specimen. In other words, stresses transfer from the concrete matrix to the fibers. As a result, the concrete specimens with fibers have higher strain tolerance than those without fibers. Gao et al. [40] achieved similar results regarding the increased splitting tensile strength of concrete containing GGBFS with steel and polypropylene fibers. Using only steel fibers, compared to the simultaneous use of steel and carbon fibers, had a more significant effect on increasing the splitting tensile strength

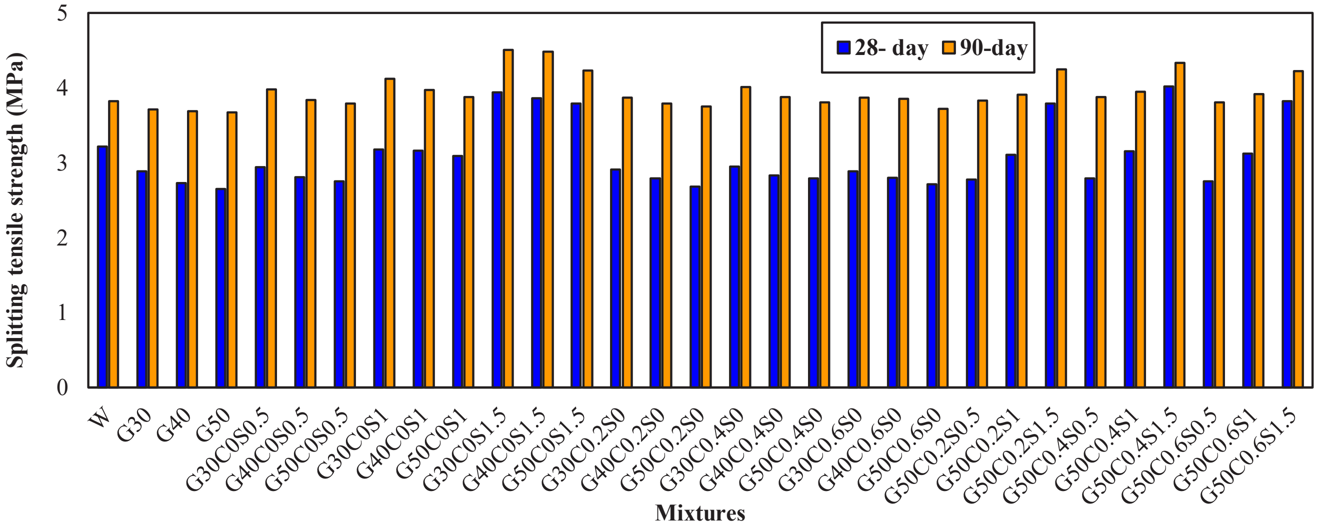


Fig. 5. The splitting tensile strength of specimens at the ages of 28 and 90 days.

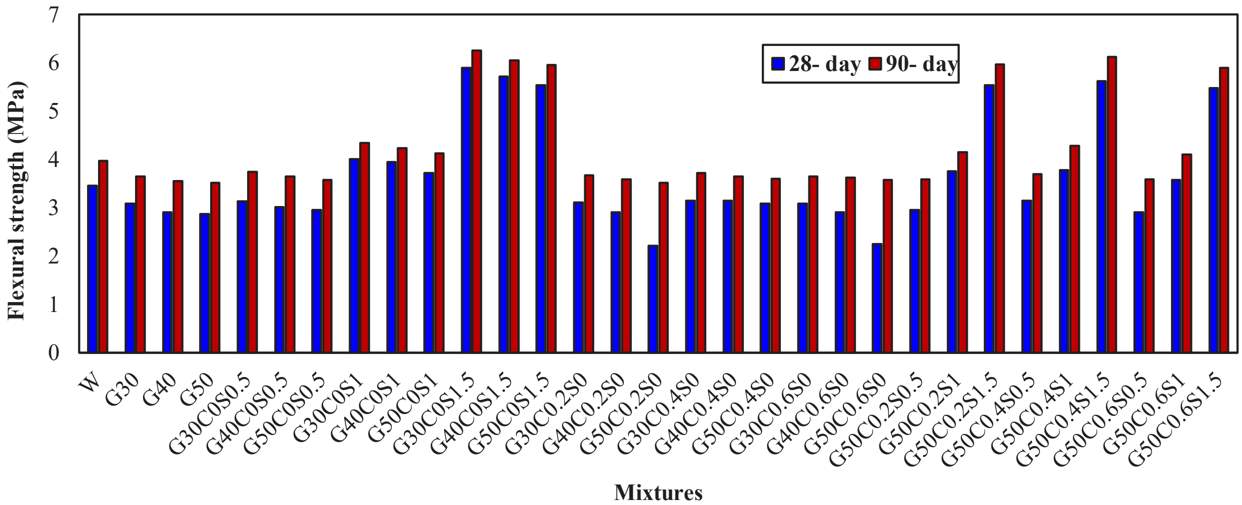


Fig. 6. The flexural strength of specimens at the ages of 28 and 90 days.

of the specimens. The splitting tensile strength of specimens with steel fibers increased possibly due to the greater length of steel fibers (50 mm in this study) than the carbon fibers (6.4 mm). Another reason was the higher involvement and consistency of the steel fibers with concrete, given their geometrical structure (the ending hooks) compared to the carbon fibers. The maximum splitting tensile strength in groups 3 to 5 with the steel fibers was observed in specimen G30C0S1.5 of group 5, with the values of 3.94 and 4.51 MPa at the ages of 28 and 90 days (increased by 22.36 and 18.06% compared to the control specimen), respectively. The specimen with 0.4% carbon fiber had the maximum splitting tensile strength in groups 6 to 8. It can be inferred that increasing the volume percentage of carbon fiber to 0.6% reduced the compressibility of the samples and increased the air pores, thus reducing the splitting tensile strength. Satisfying results were obtained for the splitting tensile strength of specimens containing the hybrid of fibers. It is worth stating that the maximum splitting tensile strength in groups 9 to 11 was observed by replacing the GGBFS and the hybrid of fibers in specimen G50C0.4S1.5, showing a rise of 24.85% (4.02 MPa) at the age of 28 days and 13.35% (4.33 MPa) at the age of 90 days compared to the control specimen.

3- 3- 3- . Flexural strength

Fig. 6 and Table 9 provide the results of the flexural strength tests on specimens at the ages of 28 and 90 days. By increasing the GGBFS from 30 to 50%, the flexural strength of specimens of group 2 decreased by 10.98, 15.90, and 17.05% at the age of 28 days and 8.06, 10.58, and 11.59%

Table 9. The flexural strength of specimens at the ages of 28 and 90 days.

Group	Mix ID	Flexural Strength (MPa)	
		28-day	90-day
1	W	3.46	3.97
2	G30	3.08	3.65
	G40	2.91	3.55
	G50	2.87	3.51
3	G30C0S0.5	3.13	3.74
	G40C0S0.5	3.01	3.65
	G50C0S0.5	2.95	3.58
4	G30C0S1	4.01	4.34
	G40C0S1	3.95	4.23
	G50C0S1	3.72	4.12
5	G30C0S1.5	5.89	6.25
	G40C0S1.5	5.71	6.05
	G50C0S1.5	5.54	5.95
6	G30C0.2S0	3.11	3.67
	G40C0.2S0	2.91	3.59
	G50C0.2S0	2.21	3.51
7	G30C0.4S0	3.15	3.72
	G40C0.4S0	3.14	3.65
	G50C0.4S0	3.09	3.60
8	G30C0.6S0	3.09	3.65
	G40C0.6S0	2.90	3.62
	G50C0.6S0	2.25	3.58
9	G50C0.2S0.5	2.95	3.59
	G50C0.2S1	3.75	4.15
	G50C0.2S1.5	5.54	5.97
10	G50C0.4S0.5	3.15	3.69
	G50C0.4S1	3.78	4.28
	G50C0.4S1.5	5.62	6.12
11	G50C0.6S0.5	2.91	3.59
	G50C0.6S1	3.58	4.10
	G50C0.6S1.5	5.48	5.89

at the age of 90 days compared to the control specimen. Similar results were presented in previous studies [41, 42]. The flexural strengths of the specimens of groups 3 to 5 and 6 to 8 increased significantly by adding (steel or carbon) fibers compared to the control specimen. In comparison with using a hybrid of steel and carbon fibers, using only steel fibers had a better performance in increasing flexural strength. The highest flexural strength observed in specimen G30C0S1.5 equaled 5.89 and 6.25 MPa (increased by 70.23 and 57.43% compared to the control specimen) at the ages of 28 and 90 days, respectively. In other words, the bridging action between the fiber and concrete increased the flexural strength of the specimens. The hybrid of steel and carbon fibers also had a significant effect on increasing the flexural strength of the specimens. As shown in Table 9, specimen G50C0.4S1.5 had the maximum flexural strength (5.62 and 6.12 MPa at the ages of 28 and 90 days, respectively) among the specimens containing GGBFS and the hybrid of steel and carbon fibers.

Table 10. The abrasion test results of specimens at the ages of 28 and 90 days.

Group	Mix ID	Abrasion (mm)					
		28-day			90-day		
		100 Cycles	200 Cycles	300 Cycles	100 Cycles	200 Cycles	300 Cycles
1	W	36.25	38.01	43.22	28.12	35.22	37.25
2	G30	35.89	38.03	43.18	27.87	35.19	37.01
	G40	34.23	37.98	42.54	27.15	35.22	36.84
	G50	34.12	37.95	41.83	27.01	35.12	36.12
3	G30C0S0.5	32.72	37.56	41.28	26.08	35.01	35.39
	G40C0S0.5	32.03	37.51	41.31	25.9	34.92	35.15
	G50C0S0.5	31.1	36.97	40.75	24.79	33.78	34.71
4	G30C0S1	29.54	35.21	39.36	24.12	32.25	33.66
	G40C0S1	29.62	34.87	38.95	24.04	32.08	33.1
	G50C0S1	28.48	34.22	38.26	23.23	31.98	32.88
5	G30C0S1.5	27.15	33.58	37.62	22.16	30.46	31.22
	G40C0S1.5	27.01	33.46	37.41	21.84	30.03	30.15
	G50C0S1.5	26.95	33.02	36.84	20.42	28.99	29.08
6	G30C0.2S0	35.89	38.01	43.18	27.79	35.18	37
	G40C0.2S0	34.2	37.95	42.52	27.15	35.25	36.83
	G50C0.2S0	34.11	37.46	41.79	27.03	35.16	36.12
7	G30C0.4S0	35.74	37.62	42.98	26.81	34.95	36.81
	G40C0.4S0	33.98	37.55	42.28	26.55	33.93	36.72
	G50C0.4S0	33.85	37.28	41.49	26.21	32.64	35.91
8	G30C0.6S0	35.88	37.65	43.16	27.75	35.2	36.98
	G40C0.6S0	34.18	37.54	42.49	27.11	35.25	36.79
	G50C0.6S0	34.09	37.43	41.78	26.98	33.03	36.08
9	G50C0.2S0.5	31.05	37.55	40.73	24.69	35.01	34.69
	G50C0.2S1	28.35	36.58	38.26	23.12	34.88	32.86
	G50C0.2S1.5	26.88	36.25	36.84	20.38	33.75	29.06
10	G50C0.4S0.5	30.85	36.52	40.61	24.02	34.25	34.62
	G50C0.4S1	28.21	36.02	38.14	22.81	33.59	32.74
	G50C0.4S1.5	26.12	35.55	36.69	20.03	31.96	28.79
11	G50C0.6S0.5	30.98	37.49	40.75	24.65	35.06	34.7
	G50C0.6S1	28.29	36.36	38.25	23.23	34.85	32.85
	G50C0.6S1.5	26.85	36.07	36.83	20.36	33.56	29.06

3- 3- 4- Abrasion test result

Fig. 7 and Table 10 show the results of the abrasion tests for 100, 200, and 300 cycles. As can be seen, increasing the number of cycles in the abrasion test from 100 to 300 increased the groove dimension of specimens. Moreover, the specimens' abrasion was significantly reduced with the rise in the concrete curing age. Comparing the abrasion of the specimens of group 2 (containing the GGBFS alternative) with the control specimen shows that increasing the GGBFS from 30 to 50% could significantly reduce the abrasion of the specimens. In this regard, abrasion reduced from 36.25 mm in the control specimen to 34.12 mm in the specimen with 50% GGBFS at the age of 28 days (reduction of 5.88%) in 100 cycles. Correspondingly, it was reduced from 28.12 mm in the control specimen to 27.01 mm (3.95% reduction) at the age of 90 days. Moreover, the abrasion in the specimen with 50% GGBFS at the ages of 28 and 90 days slightly decreased by 0.16 and 0.29%, respectively, compared to the control specimen in 200 cycles. However, the abrasion in 300 cycles in the specimen with 50% GGBFS at the ages of 28 and 90

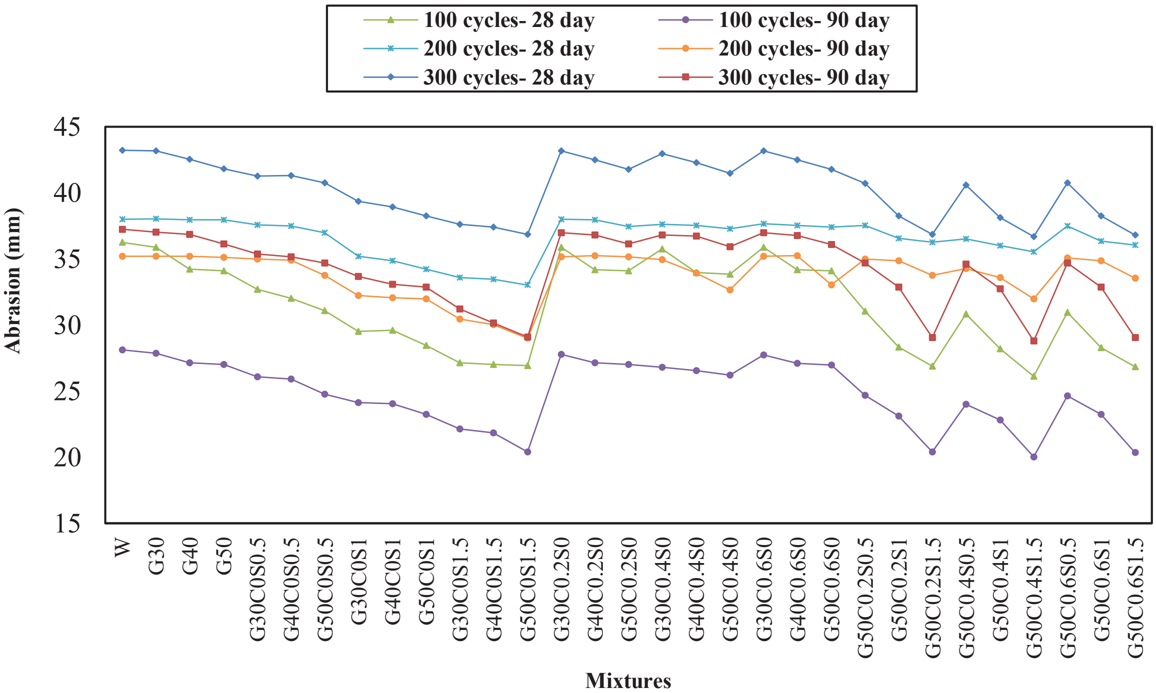


Fig. 7. The abrasion test results.

days had partial reductions of 3.22 and 3.03%, respectively, compared to the control specimen. Ozbay et al. [43] found similar results regarding the effect of GGBFS replacement. The effectiveness of the hybrid of steel fibers and GGBFS in reducing the abrasion was higher compared to that of the hybrid of carbon fibers and GGBFS. The minimum abrasion in groups 3 to 5 in 100 cycles was observed in specimen G50C0S1.5, being equal to 26.95 and 20.42 mm at the ages of 28 and 90 days (decreased by 25.66 and 27.38% compared to the control specimen), respectively. Furthermore, the minimum abrasion in groups 6 to 8 was observed in specimen G50C0.4S0 with values of 33.85 and 26.21 mm at the age of 28 and 90 days (reductions of 6.62 and 6.79% in comparison with the control specimen), respectively, in 100 cycles. The best results were observed in specimen G50C0.4S1.5 containing GGBFS and steel and carbon fibers in 100 cycles, showing reductions by 27.95% (26.12 mm) and 28.77% (20.03 mm) compared to the control specimen.

3- 3- 5- Water absorption

Fig. 8 demonstrates the water absorption results at the age of 90 days, according to which replacing a part of cement with GGBFS could significantly reduce the water absorption of specimens. For example, water absorption of group 2 (with GGBFS) reduced from 1.42 (10.69% reduction compared to the control specimen) to 1.24% (22.01% reduction compared to the control specimen). Satisfying results were obtained for the specimens with the GGBFS and steel fibers in reducing the water absorption. The minimum water absorption was observed in specimen G50C0S1.5 with a value of 0.83% (a reduction of 47.80% compared to the control specimen). Furthermore, the results of specimens with carbon fibers revealed the reduction of water absorption parameters was similar to those of the steel fiber specimens. It is worth noting that the minimum water absorption of groups 6 to 8 was recorded for specimen G50C0.4S0 with a percentage of 1.11% (30.19% reduction compared to the control specimen). Based on the results of groups 9 to 11 containing a hybrid of steel and carbon fibers and GGBFS, the best performance in water absorption belonged to specimen G50C0.4S1.5 with a percentage of 0.75% (reduction of 52.83% compared to the control specimen). It should be noted that the water absorption of all specimens was within the proper range based on CEB-FIP [44] (lower than 3%).

3- 4- Microstructure behavior of concrete containing GGBFS

The microstructures of mixtures of groups 1 and 2 were investigated using SEM FEI Quanta 200 electron microscope. An accelerating voltage of 15 kV was applied to take the SEM photos. To study the microstructure behavior of concrete containing GGBFS, fractured small-size (10×10 mm2) pieces of compressive strength specimens were taken and used for Scanning Electron Microscopy (SEM) analysis. Fig. 9 shows the SEM images of specimens taken from mixtures containing 0, 30, 40, and 50% GGBFS on a scale of 500 nm after 28 days of curing. The porosity can be observed in the SEM image of the control specimen without GGBFS (Fig. 9 (a)). Due to the reaction between sulfate ions

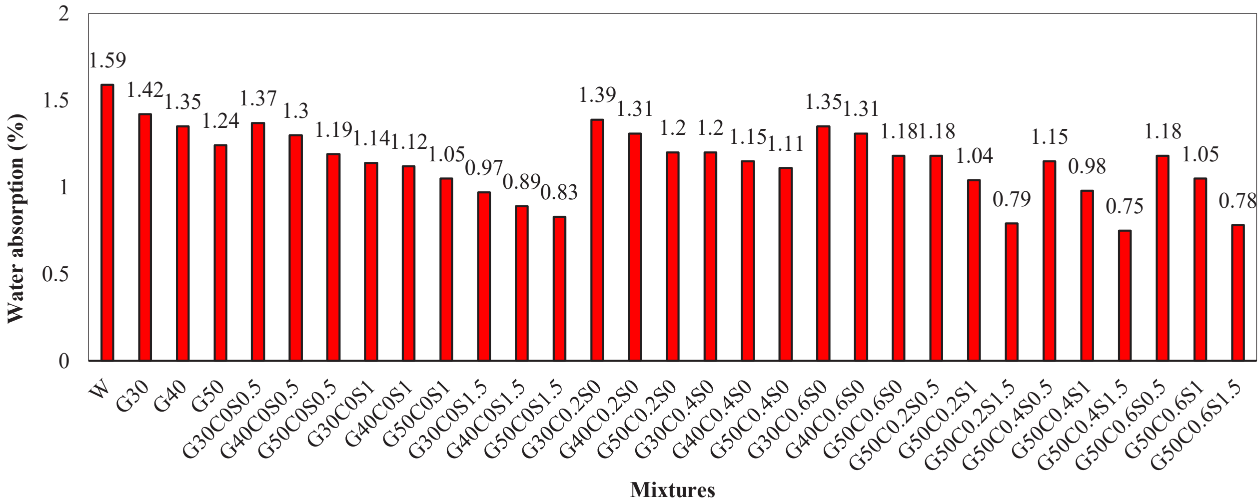
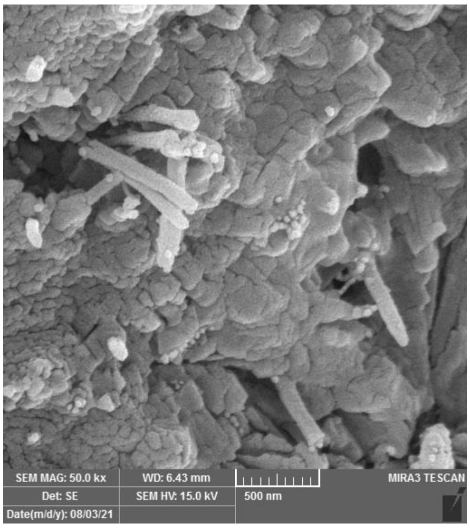
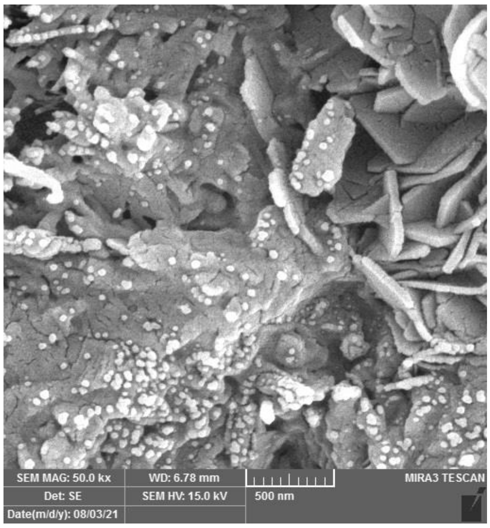


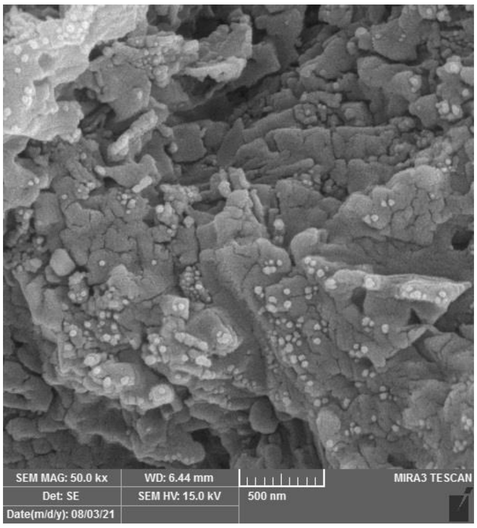
Fig. 8. The water absorption results at the age of 90 days.



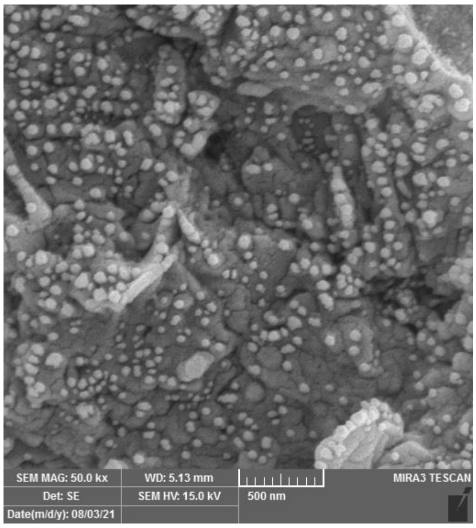
(a) Mixture without GGBFS



(b) Mixture with 30% GGBFS



(c) Mixture with 40% GGBFS



(d) Mixture with 50% GGBFS

Fig. 9. The SEM image of concrete containing GGBFS.

and the aluminate phases in cement, ettringite needle-like crystals were formed in this specimen. Fig. 9 (b-d) depicts the SEM images of the specimens with 30%, 40%, and 50% GGBFS. As it is clear, the pores are filled. With the rise in the GGBFS, the matrix became denser, thus improving the microstructure of the concrete. As can be observed from Fig. 9 (b), the specimen with 30% GGBFS had a large number of hexagonal structures of calcium hydroxide at 28 days of curing. Due to the secondary pozzolanic reaction, the calcium hydroxide crystals were converted into C-S-H gel in specimens containing 40 and 50% GGBFS. However, the C-S-H gel became more visible, as can be seen in Fig. 9 (c and d).

4- Conclusion

In the present study, the mechanical properties and durability of concrete were evaluated using steel and carbon fibers, along with GGBFS as an alternative to cement. To this end, compressive strength, splitting tensile strength, flexural strength, abrasion, water absorption, and slump tests were performed on the specimens. The densities of the concrete in the fresh and hardened states were also determined. According to the experimental studies, the following conclusions can be drawn:

Considering the lower capillary pore volume of the GGBFS compared to cement, the slump of specimens containing GGBFS (with and without fibers) was significantly decreased. The effectiveness of steel fibers was very significant in reducing slump values compared to carbon fibers. The highest slump reduction, being equal to 55 mm (35.29% decrease compared to the control specimen), was observed in the specimen with 50% GGBFS, along with 1.5% steel fibers and 0.6% carbon fiber.

The compressive strength of the specimens at the age of 28 days was reduced by 2.59, 8.74, and 17.45% (compared to that of the control specimen) at the GGBFS replacement percentages of 30, 40, and 50%, respectively. As the age of specimens increased from 28 to 90 days, the compressive strength of the specimens with 30 and 50% GGBFS grew by 2.69, 5.69, and 7.84%, respectively. Furthermore, the specimen with 50% GGBFS, 0.4% carbon fibers, and 1.5% steel fibers had the maximum compressive strength with values of 36.12 MPa at the age of 28 days (an increase of 16.93% compared to the control specimen) and 43.98 MPa at the age of 90 days (an increase of 12.74% compared to the control specimen).

The maximum splitting tensile strength was observed in the specimens with 50% GGBFS and a hybrid of 1.5% steel fibers and 0.4% carbon fibers, being equal to 4.02 MPa at the age of 28 days (an increase of 24.85% compared to the control specimen) and 4.33 MPa at the age of 90 days (an increase of 13.35% compared to the control specimen).

The flexural strength of specimens at the age of 28 and 90 days decreased by increasing the GGBFS replacement from 30 to 50% compared to the control specimen. The flexural strength significantly increased by adding (steel or carbon) fibers compared to the control specimen. It should be noted that the steel fibers were more effective than the carbon fibers in increasing flexural strength. The hybrid of 50% GGBFS with 1.5% steel fibers and 0.4% carbon fibers enhanced the specimens' flexural strength significantly at the ages of 28 and 90 days.

Increasing the number of cycles in the abrasion tests from 100 to 300 could raise the specimens' abrasion. According to the results of the abrasion tests, by increasing the concrete age from 28 to 90 days, the abrasion was significantly reduced. The rise in the GGBFS replacement from 30 to 50% also significantly reduced the specimens' abrasion. The abrasion reduction in specimens containing steel fibers and GGBFS was significantly higher than in specimens containing GGBFS and carbon fibers. The highest reduction in the abrasion was observed in the specimen with 50% GGBFS, 1.5% steel fibers, and 0.4% carbon fibers.

Adding GGBFS could significantly reduce the water absorption of specimens at the age of 90 days. The percentage of water absorption in specimens with 30 to 50% GGBFS decreased from 22.01 to 10.69% compared to the control specimen. The results of the specimens with GGBFS and steel fibers showed the positive effect of the mentioned fibers on water absorption reduction. The highest reduction in water absorption was observed in the specimen containing 50% GGBFS, 1.5% steel fibers, and 0.4% carbon fibers with water absorption of 0.75% (52.83% reduction compared to the control specimen).

SEM investigations revealed the dense microstructures of the concrete specimens containing GGBFS.

References

[1] Hwang, C.L. and Lin, C.Y. "Strength development of blended blast-furnace slag-cement mortars", Journal of the Chinese Institute of Engineers, 9(3), (1986), 233-239.

[2] Pal, S.C., Mukherjee, A., Pathak, S.R. "Investigation of hydraulic activity of ground granulated blast furnace slag in concrete", Cement and concrete research, 33(9), (2003), 1481-1486.

[3] Johari, M.M., Brooks, J.J., Kabir, S., Rivard, P. "Influence of supplementary cementitious materials on engineering properties of high strength concrete", Construction and Building Materials, 25(5), (2011), 2639-2648.

[4] Boukendakdji, O., Kadri, E.H., Kenai, S. "Effects of granulated blast furnace slag and superplasticizer type on the fresh properties and compressive strength of self-compacting concrete", Cement and concrete composites, 34(4), (2012), 583-590.

[5] Atiş, C.D., Bilim, C. "Wet and dry cured compressive strength of concrete containing ground granulated blast-furnace slag", Building and Environment, 42(8), (2007), 3060-3065.

[6] Gholampour, A., Ozbakkaloglu, T. "Performance of sustainable concretes containing very high volume Class-F fly ash and ground granulated blast furnace slag", Journal of Cleaner Production, 162, (2017), 1407-1417.

[7] Berndt, M.L. "Properties of sustainable concrete containing fly ash, slag and recycled concrete aggregate", Construction and Building Materials, 23(7), (2009),

2606-2613.

[8] Wang, H.Y., Lin, C.C. “A study of fresh and engineering properties of self-compacting high slag concrete (SCHSC) “, Construction and Building Materials, 42, (2013), 132-136.

[9] Ashish, D.K., Singh, B., Verma, S.K. “The effect of attack of chloride and sulphate on ground granulated blast furnace slag concrete”, Advances in concrete construction, 4(2), (2016), 107-121.

[10] Ghazy, M.F., Abd Elaty, M.A., Zalhaf, N.M. “Mechanical Properties of HPC Incorporating Fly Ash and Ground Granulated Blast Furnace Slag After Exposure to High Temperatures”, Periodica Polytechnica Civil Engineering, 66(3), (2022), pp.761-774.

[11] Park, S.J., Seo, M.K., Shim, H.B., Rhee, K.Y. “Effect of different cross-section types on mechanical properties of carbon fibers-reinforced cement composites”, Materials Science and Engineering: A, 366(2), (2004), 348-355.

[12] Garcés, P., Fraile, J., Vilaplana-Ortego, E., Cazorla-Amorós, D., Alcocel, E.G., Andión, L.G. “Effect of carbon fibres on the mechanical proIvorperties and corrosion levels of reinforced portland cement mortars”, Cement and concrete research, 35(2), (2005), 324-331.

[13] Yao, W., Li, J., Wu, K. “Mechanical properties of hybrid fiber-reinforced concrete at low fiber volume fraction” Cement and concrete research, 33(1), (2003), 27-30.

[14] Giner, V.T., Baeza, F.J., Ivorra, S., Zornoza, E., Galao, O. “Effect of steel and carbon fiber additions on the dynamic properties of concrete containing silica fume”, Materials & Design, 34, (2012), 332-339.

[15] Ivorra, S., Garcés, P., Catalá, G., Andión, L.G., Zornoza, E. “Effect of silica fume particle size on mechanical properties of short carbon fiber reinforced concrete”, Materials & Design, 31(3), (2010), 1553-1558.

[16] Wang, C., Li, K.Z., Li, H.J., Jiao, G.S., Lu, J., Hou, D.S. “Effect of carbon fiber dispersion on the mechanical properties of carbon fiber-reinforced cement-based composites”, Materials Science and Engineering: A, 487(1-2), (2008), 52-57.

[17] Cucchiara, C., La Mendola, L., Papia, M. “Effectiveness of stirrups and steel fibres as shear reinforcement”, Cement and concrete composites, 26(7), (2004), 777-786.

[18] Mo, K.H., Chin, T.S., Alengaram, U.J., Jumaat, M.Z. “Material and structural properties of waste-oil palm shell concrete incorporating ground granulated blast-furnace slag reinforced with low-volume steel fibres”, Journal of Cleaner Production, 133, (2016), 414-426.

[19] Ghanem, S.Y., Bowling, J. “Mechanical Properties of Carbon-Fiber–Reinforced Concrete”, Advances in Civil. Engineering Materials, 8(3), (2019), 224-234.

[20] ASTM C150-05, Standard specification for Portland cement. ASTM International, West Conshohocken, PA, USA, (2005).

[21] ASTM C494/C494M-04. Standard specification for chemical admixtures for concrete. ASTM International, West Conshohocken, PA, USA, (2004).

[22] ACI 211.1. Standard Practice for Selecting Proportions for Normal. Heavyweight, and Mass Concrete, American Concrete Institute, (2002).

[23] BS EN 12390-3. Testing Hardened Concrete. Compressive Strength of Test Specimens. British Standards, London, UK, (2009).

[24] ASTM C496/C496M-11. Standard test method for splitting tensile strength of cylindrical concrete specimens. ASTM International, West Conshohocken, PA, USA, (2011).

[25] ASTM, C1609/C1609M-19a. Standard test method for flexural performance of fiber-reinforced concrete (using beam with third-point loading), ASTM International, West Conshohocken, PA, USA, (2019).

[26] BS EN 1338. Concrete paving blocks. Requirements and test methods. British Standards, London, UK, (2003).

[27] ASTM C642-13. Standard test method for density, absorption, and voids in hardened concrete, ASTM International, West Conshohocken, PA, USA, (2013).

[28] ASTM C143/C143M-03. Standard test method for slump of hydraulic-cement concrete, West Conshohocken, PA, USA, (2003).

[29] Siddique, R., Kaur, D. “Properties of concrete containing ground granulated blast furnace slag (GGBFS) at elevated temperatures”, Journal of Advanced Research, 3(1), (2012), 45-51.

[30] Collins, F.G., Sanjayan, J.G. “Workability and mechanical properties of alkali activated slag concrete”, Cement and concrete research, 29(3), (1999), 455-458.

[31] ASTM C138/C138M-16a. Standard test method for density (unit weight), yield, and air content (gravimetric) of concrete, ASTM International, West Conshohocken, PA, USA, (2016).

[32] Zhao, H., Sun, W., Wu, X., Gao, B. “The properties of the self-compacting concrete with fly ash and ground granulated blast furnace slag mineral admixtures”, Journal of Cleaner Production, 95, (2015), 66-74.

[33] Lilkov, V., Stoitchkov, V. “Effect of the “Pozzolit” active mineral admixture on the properties of cement mortars and concretes Part 2: Pozzolanic activity”, Cement and concrete research, 26(7), (1996), 1073-1081.

[34] Nehdi, M.L., Summer, J. “Optimization of ternary cementitious mortar blends using factorial experimental plans”, Materials and Structures, 35(8), (2002), 495-503.

[35] Barnett, S.J., Soutsos, M.N., Millard, S.G., Bungey, J.H. “Strength development of mortars containing ground granulated blast-furnace slag: Effect of curing temperature and determination of apparent activation energies”, Cement and concrete research, 36(3), (2006), 434-440.

[36] Oner, A., Akyuz, S. “An experimental study on optimum usage of GGBS for the compressive strength of concrete”, Cement and concrete composites, 29(6), (2007), 505-514.

[37] Gesoğlu, M., Özbay, E. “Effects of mineral admixtures on fresh and hardened properties of self-compacting concretes: binary, ternary and quaternary systems”, Materials and Structures, 40(9), (2007), 923-937.

[38] Güneyisi, E., Gesoğlu, M. “A study on durability

properties of high-performance concretes incorporating high replacement levels of slag", Materials and Structures, 41(3), (2008), 479-493.

[39] Aghaeipour, A., Madhkhan, M. "Effect of ground granulated blast furnace slag (GGBFS) on mechanical properties of roller-compacted concrete pavement", Journal of Testing and Evaluation, 48(4), (2020), 2786-2802.

[40] Gao, D., Yan, D., Li, X. "Splitting strength of GGBFS concrete incorporating with steel fiber and polypropylene fiber after exposure to elevated temperatures", Fire Safety Journal, 54, (2012), 67-73.

[41] Sivasundaram, V., Malhotra, V.M. "Properties of concrete incorporating low quantity of cement and high volumes of ground granulated slag", Materials Journal, 89(6), (1992), 554-563.

[42] Khatib, J.M., Hibbert, J.J. "Selected engineering properties of concrete incorporating slag and metakaolin", Construction and Building Materials, 19(6), (2005), 460-472.

[43] Ozbay, E., Lachemi, M., Sevim, U.K. "Compressive strength, abrasion resistance and energy absorption capacity of rubberized concretes with and without slag", Materials and Structures, 44(7), (2011), 1297-1307.

[44] CEB-FIP, M. Design of concrete structures. CEB-FIP Model Code 1990, British Standard, London, UK, (1993).

HOW TO CITE THIS ARTICLE

S. M. Miralami, S. Hajati Ziabari, M.R. Esfahani, The Effect of GGBFS with Steel and Carbon Fibers on the Mechanical Properties and Durability of Concrete, AUT J. Civil Eng., 6(2) (2022) 319-336.

DOI: 10.22060/ajce.2023.21616.5806