ORIGINAL RESEARCH

Experimental Investigation of the Effect of Slag and Fly Ash Pozzolanic Materials as Cement Replacements on the Compressive Strength of Concrete

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Abstract:

Portland cement is one of the main materials used in the construction industry and is responsible for a significant share of global greenhouse gas emissions. Therefore, using pozzolanic materials and industrial by-products such as fly ash and blast furnace slag as partial replacements for cement is considered an effective approach toward reducing environmental impacts and promoting sustainable concrete. In this study, the compressive strength of concrete was investigated by partially replacing cement with fly ash at 10%, 20%, and 30%, and with slag at 20%, 30%, and 50%. A control mix without any pozzolanic additives was also prepared for comparison. Cube specimens were cast according to ASTM C109 and cured under laboratory conditions for 180 days. After the curing period, compressive strength tests were conducted on all samples. The results showed that incorporating fly ash and slag can improve the long-term compressive strength of concrete, although the extent of improvement depends on the replacement percentage and type of material used. According to researches done, replacing 20% of the cement with fly ash and 20% with slag resulted in the highest increase in compressive strength at 180 days compared to the control mix. The comparison indicates that these optimal replacement levels contributed effectively to pozzolanic reactions and the development of a denser microstructure over time.

Keywords:
Sustainable concrete, Fly ash, Slag, Compressive strength, Cement replacement

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1. Introduction

In recent decades, rapid population growth and unprecedented urban expansion have led to a significant increase in construction projects and the demand for concrete. Concrete, as the most widely used construction material after water, is extensively employed in infrastructure, building, transportation, and marine constructions. This surge in concrete consumption has directly resulted in a substantial rise in Portland cement production, as cement plays a crucial role in providing the mechanical properties of concrete. However, cement production is one of the most polluting industrial processes; it is estimated that the production of each ton of Portland cement results in the emission of approximately one ton of carbon dioxide (CO_2) into the atmosphere. This has made the construction industry responsible for more than 8% of global greenhouse gas emissions [1].

In response to this environmental challenge, researchers and civil engineers have been exploring solutions to reduce cement consumption and, consequently, its environmental impact. One of the most effective and cost-efficient solutions is the use of supplementary cementitious materials (SCMs) as partial replacements for cement. Among these materials, Fly Ash and Ground Granulated Blast Furnace Slag (GGBS) are among the most common and readily available options. Fly Ash, a by-product of coal combustion in power plants, has pozzolanic properties and reacts with calcium hydroxide formed during cement hydration, leading to the formation of additional C–S–H gel, which results in increased compressive strength of concrete in the medium- and long-term [2]. On the other hand, GGBS, as a pozzolanic and reactive material, not only enhances concrete strength but also significantly improves its durability against sulfate, chloride attacks, and freeze-thaw cycles [3].

Studies have shown that variations in carbon dioxide (CO_2) concentrations can negatively affect the carbonation of concrete and its strength, ultimately leading to a reduction in its mechanical properties [4,5]. Additionally, recent research has demonstrated that the addition of mineral admixtures to self-compacting concrete improves its resistance to corrosion and reduces the damage caused by this phenomenon [6]. Furthermore, the impact of environmental changes and various factors on the quality of concrete when exposed to corrosion, particularly in reinforced concrete, has been a subject of considerable attention in multiple studies [7].

Recent studies indicate that replacing 20% to 30% of cement with Fly Ash can significantly enhance concrete strength in the long term (90 to 180 days) [8]. Similarly, replacing up to 50% of cement with GGBS under severe environmental conditions demonstrates optimal performance in terms of durability and mechanical stability [9]. Moreover, the combined use of Fly Ash and GGBS, due to their synergistic effect, not only strengthens the mechanical properties of concrete but also reduces its permeability and improves its long-term durability [10,11]. However, most studies have focused on the performance of concrete at early ages (7 to 28 days), and there is limited data on the long-term behavior of concrete, particularly at 180 days with varying replacement percentages

This study is designed to examine the effect of replacing cement with GGBS and Fly Ash on the compressive strength of concrete at different ages. In this study, various replacement percentages of cement with GGBS (20%, 30%, and 50%) and Fly Ash (10%, 20%, and 30%) have been selected [2]. Concrete samples with varying cement replacement percentages using GGBS and Fly Ash have been prepared according to the desired mix design. These samples have been tested for compressive strength at 180 days after curing under standard conditions. The results of these tests were compared with reference concrete, and the optimal percentage in terms of both strength and durability was determined

2. Materials and Methods

2.1 Materials

2.1.1. Water: The water used for concrete preparation was potable tap water, meeting the quality requirements specified in ASTM C94 [13] (Table 1). This water was free from any contaminants that could adversely affect the cement hydration process.

Table 1. Chemical analysis of the water sample used in concrete specimen preparation

	PH	Cl^-	SO_4^{-2}	SO_4^{-2}	K^+	Ca^{2+}	Mg^{2+}	Total Hardness	Dissolved Solids	Suspended Solids	Electrical Conductivity	Total Alkalinity
Measured value (gr/lit)	7.1	7.56	21.4	12	4	11	30	40	23	73	226	50
Measured value (by weight%)	-	0.756	2.14	1.2	0.4	1.1	0.3	4	2.3	7.3	22.6	5

2.1.2. Cement: In this study, Type II Portland cement was used as the main binder. This type of cement is suitable for use in concrete structures where durability is essential, due to its moderate sulfate resistance and lower heat of hydration. The chemical properties of the cement show in Table 2 [14].

Table 2. Chemical analysis and specific gravity of the cement used

	TiO_2	K_2O	Na_2O	SO_3	MgO	CaO	Fe_2O_3	Al_2O_3	SiO_2	Density (Kg/m)
Cement	-	1.02	0.50	2. 50	3.40	64	4.20	5.30	21.60	3150

2.1.3. Polycarboxylate Superplasticizer: In this study, a polycarboxylate-based superplasticizer was used to enhance the workability and reduce the water-to-cement ratio. This admixture is well known for its excellent dispersing effect, which increases the flowability of concrete mixtures without negatively affecting their stability.

2.1.4. Aggregates: The fine and coarse aggregates used in this study were natural river-sourced and rounded [15] requirements for use in concrete. The physical properties of the aggregates used are shown in Table 3.

The sieve analysis of the aggregate mixture was carried out based on ISIRI 302 standard [16], and the mixing was performed according to the guidelines in the National Iranian Concrete Mix Design Plan. The results are presented in Table 4.

2.1.5. Slag: Ground granulated blast furnace slag is a byproduct of the iron-making process, obtained by rapid cooling of molten slag (its physical properties and Chemical Properties are shown in Table 5&6). This material exhibits pozzolanic properties and, when used as a partial replacement for Portland cement, improves the durability and After mixing, fresh concrete was poured into mechanical properties of concrete [17].

2.1.6 Fly Ash

Fly ash is a fine, glassy material obtained from the combustion of coal in thermal power plants (its physical and chemical properties

Table 3. Physical properties of the aggregate mixture (gravel and sand) used in this study

Aggregate Type	Dry Specific Gravity (g/cm³)	SSD Specific Gravity (g/cm³)	Fineness Modulus	Maximum Size (mm)	Nominal Maximum Size (mm)
Gravel	2.377	2.430	6.89	19 mm	19 mm
Sand	2.51	2.61	3.863	9.50 mm	4.75 mm
Mixed Gravel & Sand	2.470	2.55	4.77	19 mm	19 mm

Table 4. Sieve analysis of the aggregate mixture used

Sieve (mm)	Remaining weight(g)	% Remaining on Sieve	% Cumulative Remaining	% Passing
50.37	0.00	0.00	0.00	100.00
25.00	0.00	0.00	0.00	100.00
19.00	40.14	1.01	1.01	98.99
12.50	864.05	21.75	22.76	77.24
9.50	126.68	3.19	25.95	74.05
4.75	278.25	7.01	32.96	67.04
2.36	1082.62	27.26	60.22	39.78
1.20	718.52	18.09	78.31	21.69
0.60	342.64	8.63	86.93	13.07
0.30	265.68	6.69	93.62	6.38
0.15	181.00	4.56	98.18	1.82
0.075	55.07	1.39	99.57	0.43
Pan	17.25	0.43	100.00	0.00
Total	3971.89	100.00	–	–

are shown in Table 7&8). This material acts as a pozzolan, reacting with calcium hydroxide to form additional cementitious compounds, which enhances the strength, durability, and workability of concrete [18].

In the next step, the polycarboxylate-based superplasticizer was premixed with a specified amount of water, and this solution was gradually added to the dry materials over about 30 seconds. Wet mixing was then

Table 5. General Physical Properties of Slag Pozzolan

Property	Smoothness coefficient	Particle brightness	The color of the particles	Physical form	Bulk density	Density
Value	۴۶۰۰	79 to 82	Grayish	Powder	۰,۳ to ۰,۴۰	2.56 (gr/cm3)

Table 6. General Chemical Properties of Slag

Component	SiO2	Al2O3	Fe2O3	CaO	MgO	MnO2	BaO	K2O	SO3	TiO2	Na2O	LOI	SrO	P2O5
wt.%	۳۵,۹۰	۸,۴۰	۰,۶۰	۳۷,۹۰	۸,۹۰	1.50	2.10	۰,۷۰	۰,۷۰	۱,۹۰	۰,۳	۰,۹۰	0.20	< 0.01

Table 7. General Physical Properties of Fly Ash Pozzolan

Property	Specific Gravity	Specific Surface Area	Particle Size (μm)	Particle Color	Particle Brightness
Value	2.30 g/cm³	20,000 m²/kg	0.02 to 0.05	Whitish	79 to 82

continued for 3 to 5 minutes to ensure a homogeneous and workable concrete mix. standard cube molds of dimensions 10×10×10 cm. Each mold was filled in three layers, and each layer was compacted thoroughly using a standard 16-mm diameter steel rod to eliminate air voids. The top surface of each sample was leveled using a metal trowel. The specimens were then stored for 24 hours at ambient temperature under moist, covered

Concrete Mixing and Curing

3.1. Concrete Mixing and Sampling:

The concrete was prepared by initially dry mixing the materials including fine and coarse river-rounded aggregates, Type II Portland cement, fly ash, and blast furnace slag (as per Table 9). This dry mixing process was carried out in a concrete mixer for approximately 2 minutes to achieve uniform distribution of the solid components.

Table 8. General Chemical Composition of Fly Ash Pozzolan

Component	LOI	Na_2O	TiO_2	SO_3	K_2O	MgO	CaO	Fe_2O_3	Al_2O_3	SiO_2
wt.%	1.8 wt.%	0.45 wt.%	1.31 wt.%	0.09 wt.%	1.65 wt.%	1.64 wt.%	2.28 wt.%	5.37 wt.%	25.37 wt.%	59.48 wt.%

Table 9-Mix Design of Concrete Samples

Mix design	Cement (%)	Slag (%)	Fly Ash (%)	Cement (kg)	Slag (kg)	Fly Ash (kg)	Water(kg)	Superplasticizer (kg)	Total Aggregate (kg)
OPC	100	0	0	400	0	0	160	4	1767
SL20	80	20	0	320	80	0	160	4	1774
SL30	70	30	0	280	120	0	160	4	1777
SL50	50	50	0	200	200	0	160	4	1783
FA10	90	0	10	360	0	40	160	4	1755
FA20	80	0	20	320	0	80	160	4	1743
FA30	70	0	30	280	0	120	160	4	1731

conditions (with wet plastic sheeting) before being transferred for curing.

3.2. Curing Procedure: After 24 hours, the molds were removed and the specimens were placed in a curing tank containing saturated limewater. The curing temperature was maintained at 20 ± 2 °C throughout the entire curing period in accordance with ASTM C511 standards [19], providing optimal conditions for continued hydration and strength gain. Curing was continued until the age of 180 days, after which the specimens were removed from the tank and prepared for compressive strength testing.

4. Compressive Strength Test of Concrete

To evaluate the mechanical performance of concrete containing pozzolans, the compressive strength test was conducted in accordance with the requirements of ASTM C39/C39M [20]. This test was performed on cubic samples with dimensions of 10×10×10 cm, which were prepared at 180 days of curing age. Three samples were used for each mix design to ensure reliable average results.

Before the test, the samples were removed from the curing tank containing saturated limewater and left at room temperature for approximately one hour to equilibrate with the environment. The surfaces of the samples were then cleaned with a moist cloth to remove any contaminants or residual layers, ensuring a uniform contact between the sample surface and the loading plate of the testing machine.

The test was conducted using a hydraulic compression testing machine with a capacity of 2000 KN, which is capable of continuously and accurately recording the loading up to the point of failure. The samples were placed centrally in the machine to ensure alignment with the load axis. The loading was applied continuously at a rate of approximately 0.25 ± 0.05 MPa per second to ensure uniform stress distribution across the sample. The loading continued until the axial strain of the concrete reached approximately 0.003 to 0.0035, at which point the sample failed. This point was considered as the final failure criterion. After failure, the maximum force applied was divided by the cross-sectional area (100 cm²), and the compressive strength of the sample was calculated in megapascals (MPa).

5. Analysis of the Results

In this study, the compressive strength of seven different mix designs, including the control mix (OPC) and six mixes containing pozzolans of blast furnace slag (SL20, SL30, SL50) and fly ash (FA10, FA20, FA30), was evaluated at 180 days (Figure 1). Each mix consisted of three standard cubic samples, and their compressive strengths were reported as averages (Figure 2). The comparison of

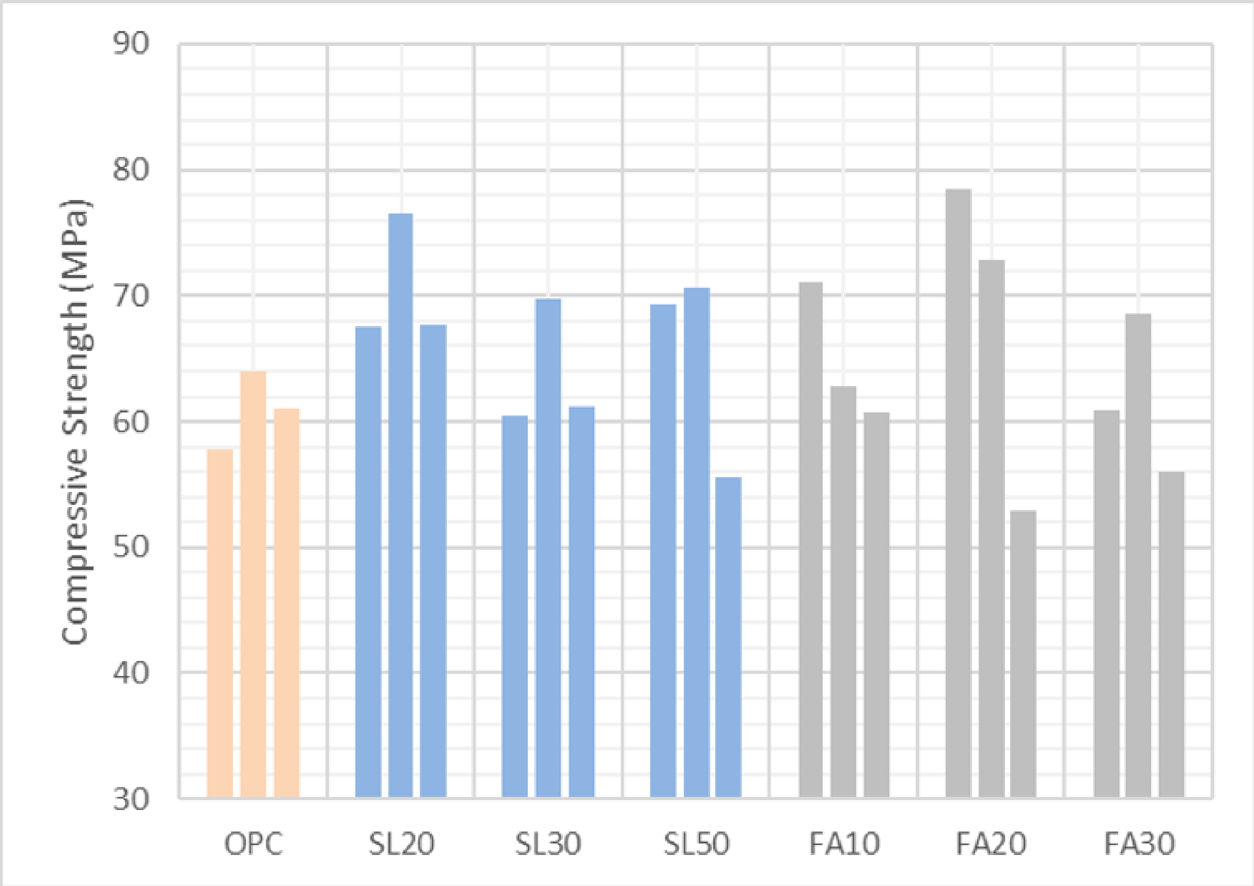

Figure 1. Compressive Strength of the Concrete Samples

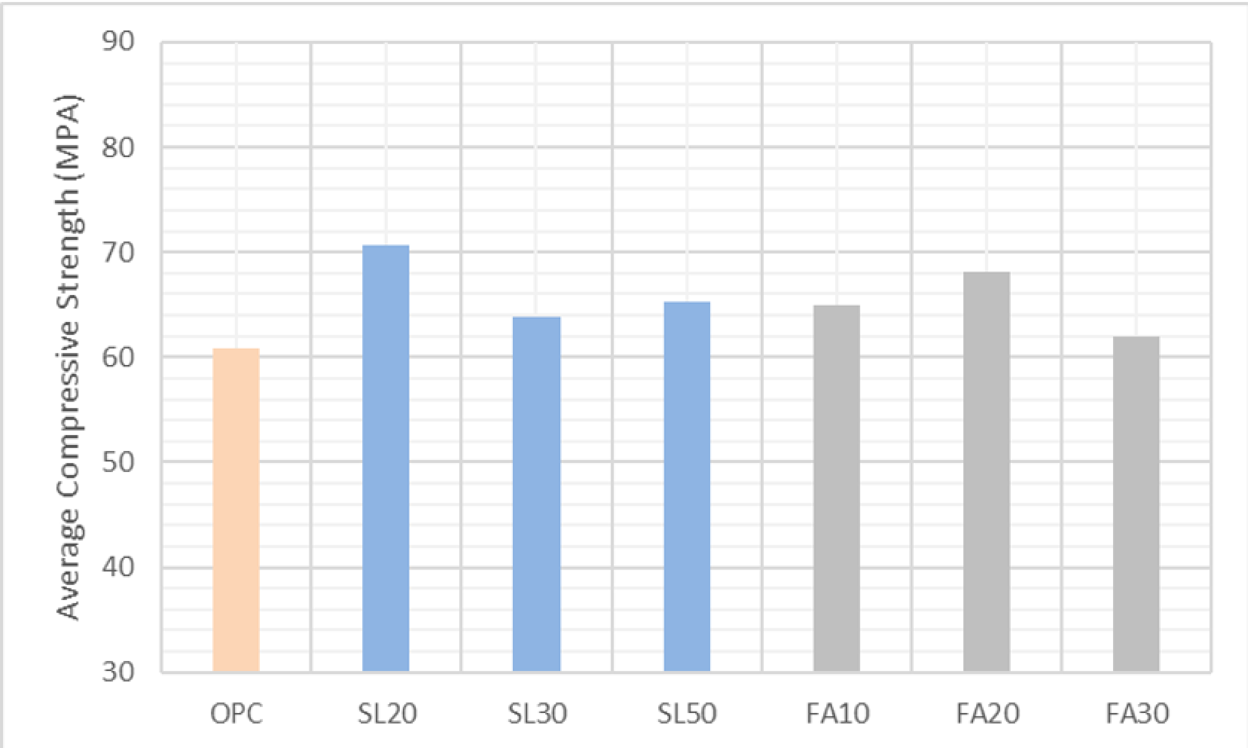

Figure 2. Average Compressive Strength of the Concrete Mixes

results indicates that all pozzolan-containing mixes performed equally or better than the ordinary Portland cement (OPC) concrete.

In the slag group, the SL20 mix, with 20% cement replaced by slag, recorded the highest compressive strength with an average of 70.6 MPa. This represents an increase of approximately 15.9% compared to the control mix (60.9 MPa). As the slag content was increased to 30% (SL30), the compressive strength reached 63.8 MPa, still 4.8% higher than OPC. In the SL50 mix, with 50% replacement, the average strength reached 65.2 MPa, which is 6.9% higher than the control mix. Therefore, replacing 20% of the cement with slag provided the greatest improvement in strength.

Regarding fly ash, it was observed that the FA20 mix, with an average compressive strength of 68.1 MPa, was 11.8% higher than OPC. The FA10 mix also showed an increase of 6.6%, with a compressive strength of 64.9 MPa compared to the control mix. However, in the FA30 mix, the strength decreased to 61.8 MPa, with only a 1.5% increase. Therefore, replacing 10% to 20% of the cement with fly ash provided more favorable results, but at higher percentages, the positive effect may decrease.

In terms of performance stability, the OPC and SL20 mixes showed the least deviation between samples, demonstrating higher reliability. In contrast, the FA20 mix, despite having a high average strength, exhibited significant fluctuations in the data, which may be due to uneven particle distribution or the greater sensitivity of fly ash to mixing conditions. Overall, the targeted use of pozzolans around 20% can help improve the compressive strength of concrete while also enhancing its long-term stability and durability.

5. Conclusions

The results of this study clearly demonstrate that partial replacement of Portland cement with supplementary cementitious materials such as Ground Granulated Blast Furnace Slag (GGBS) and Fly Ash (FA) is not only environmentally and economically justified, but also technically effective in maintaining or even improving the compressive strength of concrete at later ages. The 180-day compressive strength tests revealed that the mix containing 20% GGBS (SL20) achieved the highest strength of 70.6 MPa, showing an approximately 15.9% increase compared to the control mix (60.9 MPa). This improvement can be attributed to the enhanced formation of binding phases like calcium silicate hydrate (C–S–H) and a using GGBS and Fly Ash reduces clinker consumption and thus significantly decreases CO_2 emissions. Considering that cement production is one of the major global sources of CO_2 emissions, adopting such alternative binders plays a key role in reducing the environmental impact of construction activities. Furthermore, since these materials

recommended as optimal for achieving a balance between mechanical performance, durability, and cement reduction. Widespread use of these blends could serve as a practical and effective strategy to meet sustainable development goals, lower greenhouse gas emissions, and enhance long-term structural performance. Future research is recommended to evaluate the behavior of such mixes under varying environmental conditions, their impact on other concrete properties (such as shrinkage, creep, and chemical resistance), and a comprehensive cost-benefit analysis in real construction projects. are by-products of industrial processes, their utilization in concrete contributes to material recycling and minimizes industrial waste.

Ultimately, the study concludes that mixes with 20% GGBS and 10% Fly Ash provide the best compressive performance at 180 days. Therefore, these replacement levels are denser microstructure, which collectively enhance durability and mechanical strength. In the Fly Ash group, the FA10 mix (10% FA replacement) also outperformed the control, reaching a compressive strength of 65.2 MPa, indicating that this replacement level is optimal. However, higher replacement levels—particularly FA30—resulted in reduced compressive strength (55.7 MPa), likely due to slower pozzolanic reactions and dilution of the cementitious matrix over time. These results are consistent with previous studies and highlight the importance of identifying an optimal replacement percentage from a sustainability perspective

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