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EXPERIMENTAL INVESTIGATION ON HIGH-PERFORMANCE CONCRETE USING INDUSTRIAL WASTE MATERIALS

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Abstract

The purpose of this research is to examine the feasibility of partially replacing cement in M60 HPC with fly ash (FA) and ground granulated blast furnace slag (GGBS). We tested the workability, compressive strength, split tensile strength, flexural strength, and water absorption of five different mixtures that contained varying amounts of FA-GGBS:0%, 10%, 20%, 30%, And 40%. In terms of overall performance, the results show that the 30% replacement level was the best. This level achieved a 28-day compressive strength of 83.1 MPa, which is higher than the control mixture's 71.4 MPa. Additionally, it enhanced tensile and flexural strength and reduced water absorption. Using less cement and more sustainable industrial by-products, the results show that FA and GGBS can improve HPC performance.

Keywords: *High-Performance Concrete, Fly Ash, GGBS, Industrial Waste, Compressive Strength, Sustainability.*

1. INTRODUCTION

Concrete is one of the most widely used construction materials because of its strength, versatility and durability. The growing demand for high-performance concrete (HPC) has increased the need for materials that provide improved strength and durability while reducing environmental impacts. Conventional cement-intensive concrete consumes significant natural resources and contributes to greenhouse-gas emissions, creating a need for sustainable alternatives.

Fly ash (FA) and ground granulated blast furnace slag (GGBS) are industrial by-products that can be used as supplementary cementitious materials. Their incorporation into concrete can reduce cement consumption, utilize industrial waste and improve strength and durability when used at suitable replacement levels. However, excessive replacement may adversely affect early-age strength and workability. Therefore, determining an optimum replacement level is essential.

The present study experimentally investigates the effect of combined FA and GGBS replacement on M60-class high-performance concrete. Five mixtures, including a control mixture and four mixtures with different replacement levels, are evaluated in terms of workability, compressive strength, tensile strength, flexural strength and water absorption..

1.1 Background of the Study

The growing demand for sustainable construction materials has increased interest in using industrial by-products such as fly ash (FA) and ground granulated blast furnace slag (GGBS) in concrete. Their incorporation can reduce cement consumption, utilize industrial waste and improve the strength and durability of concrete. However, their performance depends on factors such as replacement level, water-to-binder ratio, curing conditions and admixture dosage. In the present study, cement is partially replaced with equal proportions of FA and GGBS while maintaining the major mix parameters constant. The effect of this replacement is evaluated through workability, compressive strength, split tensile strength, flexural strength and water absorption to determine the optimum FA-GGBS proportion for high-performance concrete.

1.2 Research Objectives of the Study

The study is guided by the following objectives:

- To develop M60-grade high-performance concrete incorporating fly ash and GGBS as partial replacements for cement at different replacement levels.
- To experimentally evaluate the effect of FA-GGBS incorporation on the workability and mechanical properties, including compressive, split tensile and flexural strength, of high-performance concrete.

- To assess the water absorption characteristics of FA-GGBS-based high-performance concrete and determine the optimum replacement level based on its overall performance.

2. LITERATURE REVIEW

Khankhaje et al. (2024), who examined the use of industrial supplementary cementitious materials in concrete, fly ash, GGBS, silica fume, and metakaolin are significant substitutes for traditional cement. Physical and chemical properties, replacement percentage, and concrete composition are the three most important factors influencing the performance of industrial by-products, as their studies demonstrated. Also highlighted in the analysis were the environmental benefits of using less Portland cement..

Kumar and Deep (2023) evaluated the performance of normal concrete with that of concrete that contained GGBS and fly ash. The effectiveness of cementitious systems that use industrial by-products was proven by their research. The research showed that blended binders are a good way to recycle industrial waste while also adding strength to your projects.

Peteti et al. (2022) examined the strength characteristics of concrete that contained fly ash and GGBS. Their experiments showed that concrete's performance can be enhanced by using suitably chosen replacement amounts of extra cementitious materials, which they found to have an effect on mechanical qualities. Another key observation was how blended cement systems are affected by curing conditions.

Cheruvu and Rao (2024) looked at how well fly ash and GGBS mixed concrete performed. The study found that blended extra cementitious materials can affect the strength and transport qualities of concrete, taking mechanical and durability-related parameters into account. Instead of relying only on compressive strength, their analysis shows that other performance measures are more important.

Hawileh et al. (2025) examined how fly ash affects the compressive strength of ultra-high-performance concrete. Significant factors such as replacement level, curing age, particle properties, and superplasticizer dosage were emphasised by the authors. Their research proved that, with the right proportions, fly ash can make high-performance concrete that is both environmentally friendly and effective.

3. RESEARCH METHODOLOGY

This study looked into how different types of industrial waste affected the performance of HPC using an experimental methodology that was carried out in a controlled environment. Partial substitutions for regular Portland cement were chosen from ground granulated blast furnace slag (GGBS) and fly ash (FA). Concrete mixes with varying amounts of FA and GGBS were compared to a control mixture that did not contain any industrial waste materials. Water absorption, compressive strength, flexural strength, and split tensile strength were the primary areas of inquiry for freshly mixed concrete.

3.1 Research Design

The study utilised a comparative experimental design. We made five different batches of concrete: one control (M0) and four other modified ones (M1–M4). At10%,20%,30%, and 40% total replacement levels, fly ash and GGBS were used in equal proportions to replace cement.

Table 1: Experimental Mix Design

Mix	Total FA+GGBS Replacement	Fly Ash	GGBS
M0	0%	0%	0%
M1	10%	5%	5%
M2	20%	10%	10%
M3	30%	15%	15%
M4	40%	20%	20%

The analysis took into account a high-performance concrete of the M60 class. While considering the aggregate needs, the mix proportioning was designed in accordance with IS 10262:2019. They kept the water-to-binder ratio around 0.30 and the total binder content about 500 kg/m³. Trial batches in the lab were to verify the final proportions.

3.2 Materials Used

Standard Portland cement, fly ash, ground-granulated blast furnace slag, fine and coarse aggregate, water, and a superplasticizer based on polycarboxylate ether were the components utilised in the study. The main binder was cement, with additional cementitious ingredients including fly ash and GGBS. A combination of fine aggregate and coarse aggregate with a notional maximum size of 20 mm was utilised for the aggregate fractions. Both the mixing and curing processes utilised water of potable quality. The necessary workability was achieved with a low water-to-binder ratio by utilising a high-range water-reducing admixture.

During the mix proportioning process, the physical qualities of the ingredients were taken into account. These properties included specific gravity, fineness, grading, and water absorption.

3.3 Mix Proportioning

The proportions of the concrete mixtures were determined by gradually substituting fly ash and GGBS for cement, while keeping the overall binder content constant.

Table 2: Proposed Mix Proportions per Cubic Metre

Mix	Cement (kg)	Fly Ash (kg)	GGBS (kg)	Water (kg)	Fine Aggregate (kg)	Coarse Aggregate (kg)
M0	500	0	0	150	650	1050
M1	450	25	25	150	650	1050
M2	400	50	50	150	650	1050
M3	350	75	75	150	650	1050
M4	300	100	100	150	650	1050

It is recommended to modify the suggested ratios based on the real characteristics of the laboratory materials as they were only experimental proportions. To make meaningful comparisons, the aggregate quantities and water-to-binder ratio were kept constant throughout all of the combinations.

3.4 Specimen Preparation and Curing

To achieve a consistent concrete mixture, the necessary ingredients were first measured and combined in a laboratory mixer. Next, water and superplasticizer were added gradually. To conduct compressive, split tensile, and flexural strength testing, standard prisms, 150 × 300 mm cylinders, and workability tests on fresh concrete were used, respectively. The specimens were demoulded and water-cured in a controlled environment after initial setting and compaction. On day 28, we measured water absorption, flexural strength, and split tensile strength; on days 7, 28, and 56, we measured compressive strength.

3.5 Experimental Tests

We compared the properties of the wet and dry concrete mixes using standard laboratory procedures. The workability after mixing was assessed using immediate slump/slump-flow testing. After7,28, and 56 days, the compressive strength was measured using specimens that were 150 mm cube in size. At the 28-day mark, the split tensile strength of cylindrical specimens and the flexural strength of prism specimens were measured. To determine the amount of water absorbed, the specimens were oven-dried and subsequently saturated after 28 days. We compared the means after evaluating triplicate specimens for each condition.

3.6 Data Analysis

There was a combination of descriptive and comparative analysis done on the experimental data. Strength and water absorption reduction were measured as percentages relative to the control. Workability, compressive strength, split tensile strength, flexural strength, and water absorption were all taken into account to determine the ideal replacement amount. In cases where there were enough replicate data, the statistical significance of the differences may be evaluated using one-way ANOVA with a 5% significance threshold.

4. RESULTS AND DISCUSSION

An experimental study was conducted to assess the impact of fly ash (FA) and ground-granulated blast furnace slag (GGBS) on the fresh and hardened characteristics of high-performance concrete. The five combinations (M0-M4) were evaluated with varying amounts of total FA-GGBS replacement:0%, 10%, 20%, 30%, and 40%. In order to find the best mixture and understand how the replacement amount affected the workability, compressive strength at7,28, and 56 days, 28-day split tensile and flexural strength, and water absorption were all measured.

4.1 Workability of Fresh Concrete

The workability of the fresh concrete mixtures was evaluated immediately after mixing using slump-flow measurement. The results obtained for the five mixtures are presented in Table 4.1.

Table 3: Workability of Fresh Concrete

Mix	Total FA-GGBS Replacement (%)	Slump Flow (mm)
M0	0	690
M1	10	700
M2	20	710
M3	30	715
M4	40	705

Up to a 30% replacement level, the results show that both FA and GGBS increased the workability of fresh concrete. As a result of the blended binder's properties, the slump flow improved, going from 690 mm for M0 to 715 mm for M3. It appears that particle packing and water demand may be affected by excessive replacement, since the value marginally dropped to 705 mm after 40% replacement. With the right amount of admixture and water-to-binder ratio management, FA-GGBS integration kept workability satisfactory.

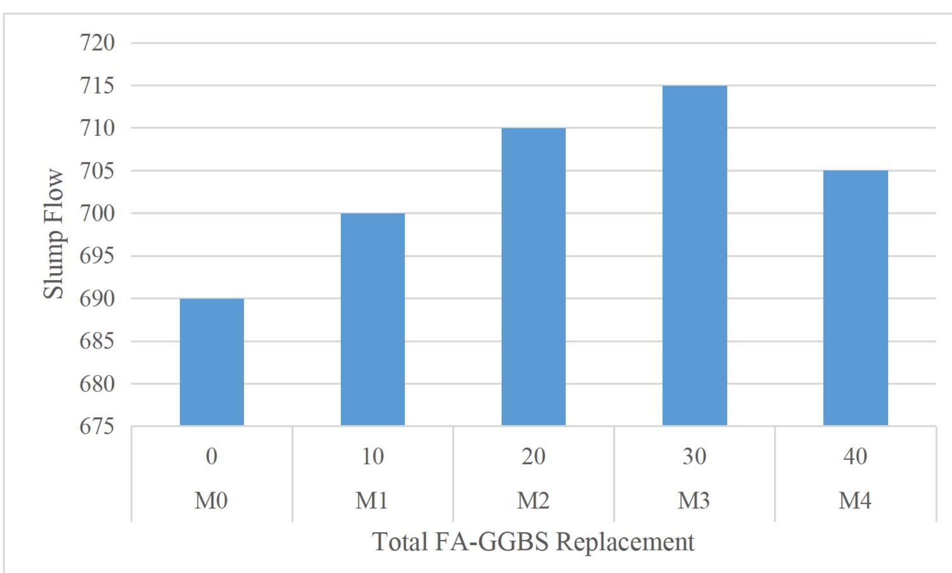

Figure 1: Variation in Workability of Fresh Concrete with FA-GGBS Replacement

4.2 Compressive Strength

Compressive strength is the primary mechanical property used to assess the structural performance of high-performance concrete. The compressive strength of the five mixtures was determined at 7, 28 and 56 days.

Table 4: Compressive Strength of Concrete

Mix	Replacement (%)	7 Days (MPa)	28 Days (MPa)	56 Days (MPa)
M0	0	55.2	71.4	75.8
M1	10	53.9	74.8	80.2
M2	20	54.8	79.6	84.9
M3	30	57.3	83.1	88.7
M4	40	55.6	77.5	83.1

At 30% replacement, the results demonstrated that FA and GGBS significantly enhanced later-age compressive strength. Strength varied between 53.9 and 57.3 MPa after 7 days, and it rose from 71.4 MPa for M0 to 83.1 MPa for M3 after 28 days, an improvement of 16.4%. Particle packing improvements, additional cementitious reactions, and matrix refining are the reasons for the rise. The strength dropped to 77.5 MPa at 40% replacement, suggesting that too much cement replacement would diminish performance. After 56 days of curing, M3 reached its maximum strength of 88.7 MPa, proving that its strength continued to increase. According to the results of the compressive strength test, the ideal level of total FA-GGBS replacement is 30% (15% FA + 15% GGBS).

4.3 Effect on Split Tensile Strength

Split tensile strength was determined at 28 days to assess the influence of FA-GGBS replacement on the tensile resistance of concrete.

Table 5: 28-Day Split Tensile Strength

Mix	Replacement (%)	Split Tensile Strength (MPa)	Change Compared with M0 (%)
M0	0	4.85	0.0
M1	10	5.02	+3.5
M2	20	5.25	+8.2
M3	30	5.48	+13.0
M4	40	5.22	+7.6

It was a steady rise from M0 to M3 in terms of split tensile strength. In contrast to the 30% replacement mixture's 5.48 MPa, the control mixture's reading was 4.85 MPa.

An enhanced cementitious matrix and better aggregate-cement paste bonding could be responsible for the increase in tensile strength. It is possible that the additional processes linked to FA and GGBS help purify the matrix and increase its resilience to tensile cracking.

The comparison with M3 revealed a decrease to 5.22 MPa with the 40% replacement mixture. Still, it outperformed the control mixture in terms of strength. According to the results, it is better to replace FA-GGBS moderately rather than excessively.

At 30% total FA-GGBS replacement, which is 15% FA and 15% GGBS, the maximum split tensile strength was achieved.

4.4 Effect on Flexural Strength

Flexural strength was evaluated at 28 days to determine the effect of industrial waste incorporation on the bending resistance of HPC.

Table 6: 28-Day Flexural Strength

Mix	Replacement (%)	Flexural Strength (MPa)	Improvement Compared with M0 (%)
M0	0	6.25	0.0
M1	10	6.48	3.7
M2	20	6.72	7.5
M3	30	7.05	12.8
M4	40	6.76	8.2

An analogous pattern to that of split tensile and compressive strengths was observed in the flexural strength as well. Flexural strengths of 6.25 MPa were observed in the control concrete, while M1, M2, and M3 showed increases to 6.48 MPa, 6.72 MPa, and 7.05 MPa, respectively.
M3 exhibited the highest flexural strength. It appears that the cementitious matrix can be improved with the right mix of FA and GGBS, since there was a 12.8% improvement compared to the control.

The decrease in flexural strength at 40% replacement further proves that adding more cementitious materials than what's optimal might not improve the mechanical properties of the concrete.
M3 is the top-performing combination according to the combined compressive, split tensile, and flexural strength findings.

4.5 Water Absorption

Water absorption was evaluated at 28 days as a durability-related indicator of the accessible pore structure of the hardened concrete.

Table 7: 28-Day Water Absorption

Mix	Replacement (%)	Water Absorption (%)	Reduction Compared with M0 (%)
M0	0	3.80	0.0
M1	10	3.50	7.9
M2	20	3.20	15.8
M3	30	2.90	23.7
M4	40	3.10	18.4

Up to 30% FA-GGBS replacement resulted in a decrease in water absorption. M3 had the lowest water absorption at 2.90%, while the control combination recorded a value of 3.80%.
A denser internal matrix and less accessible porosity may have been contributed to by the integration of FA and GGBS, as indicated by the approximately 23.7% reduction compared with the control.

The supplemental materials' secondary cementitious reactions may be responsible for the enhancement; these reactions can refine the pore structure and produce more reaction products.
Water absorption rose to 3.10 percent at 40% replacement, which was still lower than the control combination, but it was an improvement. The results show that the 30% replacement level yielded the best overall response once again.

It is important to remember that water absorption is just one factor among several when evaluating concrete's durability. Sorptivity, chloride permeability, sulphate resistance, and carbonation are other tests that could be used to analyse durability more thoroughly.

4.6 Comparative Performance of Concrete Mixtures

The overall performance of the five mixtures was compared using the principal experimental parameters.

Table 8: Overall Performance Comparison

Property	M0	M1	M2	M3	M4	Optimum
28-day compressive strength (MPa)	71.4	74.8	79.6	83.1	77.5	M3
28-day split tensile strength (MPa)	4.85	5.02	5.25	5.48	5.22	M3
28-day flexural strength (MPa)	6.25	6.48	6.72	7.05	6.76	M3
Slump flow (mm)	690	700	710	715	705	M3
Water absorption (%)	3.80	3.50	3.20	2.90	3.10	M3

Based on the comparison results, it is evident that M3 offered the best overall performance.
Fly ash and GGBS made up 15% of the 30% total industrial waste materials in the M3 combination.
Its compressive strength, split tensile strength, and flexural strength were the highest after 28 days. Among the combinations tested, it had the lowest water absorption and the largest slump flow.
Despite having more industrial waste, M4 performed worse than M3 on the majority of the characteristics that were tested. Consequently, the level of performance achieved by concrete may not be directly proportional to the amount of waste materials used to make it.

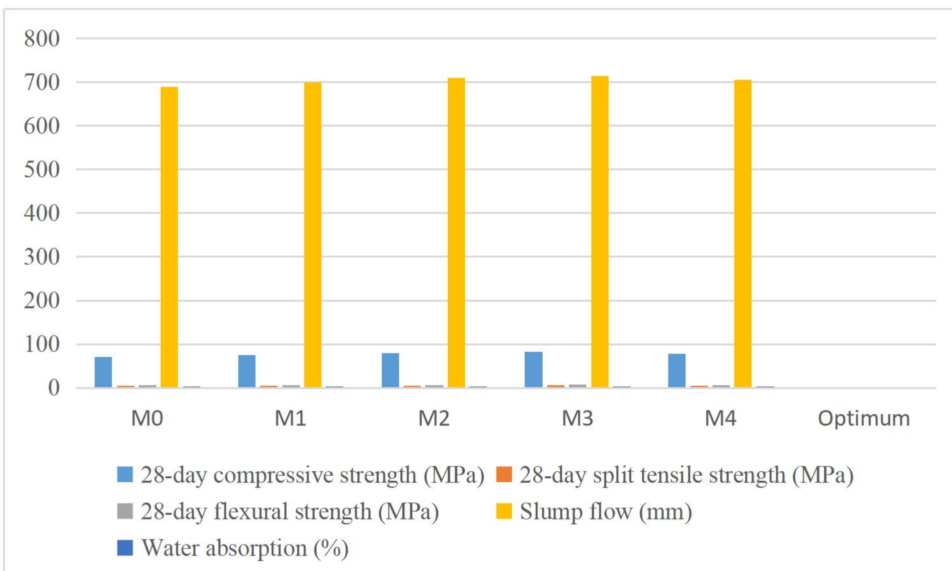

Figure 2: Overall Performance of Concrete Mixtures at Different FA-GGBS Replacement Levels

4.7 Discussion

The experimental findings show that both the fresh and hardened properties of high-performance concrete are significantly affected by the addition of fly ash (FA) and GGBS. The findings show that moderate replacement levels outperform excessive replacement levels in terms of overall performance. Due to enhanced particle packing, more cementitious reactions, and concrete matrix refinement, compressive strength increased gradually up to the 30% replacement level. Even tho the strength of some blended combinations was slightly reduced at 7 days, there was a significant increase in strength at 28 and 56 days after continuing to cure.

M3, which consisted of 15% fly ash and 15% GGBS, outperformed all of the other combinations. Although it absorbed the least amount of water, it had the greatest compressive, split tensile, and flexural strengths. More cementitious products and a denser internal matrix may have contributed to the increased strength. When compared to this, the performance drop at 40% replacement suggests that using too much cement would dilute the mixture and lessen Portland cement's role in early hydration.

Further evidence of enhanced matrix compactness and decreased accessible porosity is the decrease in water absorption at moderate replacement levels. Using FA and GGBS can lessen the need for traditional cement while also making good use of industrial waste, which is great news for environmentalists. Materials' origin, particle size, and chemical properties, in addition to curing circumstances and admixture dosage, could affect the ideal replacement amount. The results show that out of all the mixes tested, 30% FA-GGBS replacement (15% FA + 15% GGBS) gives the most balanced performance.

5. CONCLUSION

The present study investigated the effect of incorporating fly ash (FA) and ground granulated blast furnace slag (GGBS) as partial cement-replacement materials in high-performance concrete. Five concrete mixtures with 0%, 10%, 20%, 30% and 40% total FA-GGBS replacement were considered and evaluated in terms of workability, compressive strength, split tensile strength, flexural strength and water absorption. The results indicate that the incorporation of industrial waste materials can improve the performance of HPC when used at an appropriate replacement level. Among the investigated mixtures, the 30% replacement mixture containing 15% fly ash and 15% GGBS demonstrated the most favourable overall performance, achieving the highest 28-day compressive strength, split tensile strength and flexural strength, together with improved workability and the lowest water absorption. The 28-day compressive strength increased from 71.4 MPa for the control mixture to 83.1 MPa for the 30% replacement mixture, while water absorption decreased from 3.80% to 2.90%. However, increasing the replacement level to 40% resulted in a reduction in performance compared with the 30% mixture, indicating that excessive replacement may not provide additional benefits. The study therefore demonstrates the potential of FA and GGBS as sustainable supplementary cementitious materials for producing high-performance concrete while reducing dependence on conventional cement and promoting productive utilization of industrial by-products. Further experimental investigations involving durability testing, microstructural analysis, long-term curing and statistical validation are recommended to confirm and extend these findings.

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