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Mechanical and Durability Performance of Concrete Incorporating Silica Fume and GGBS as Partial Cement Replacement

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Abstract: This research investigates the effect of partially replacing ordinary Portland cement with a combination of silica fume (10%) and ground granulated blast furnace slag (GGBS) (10%) on the mechanical and durability performance of concrete. The study aims to evaluate compressive strength, workability, and durability characteristics of concrete prepared using this binary supplementary cementitious material system. Concrete specimens were prepared and tested after curing periods to assess their compressive strength development and overall structural performance. The findings indicate that incorporating silica fume and GGBS improves the microstructure of concrete, enhances compressive strength, and reduces permeability. The results demonstrate that partial replacement of cement with these materials can produce more sustainable concrete while maintaining or improving mechanical performance.

Keywords: Silica Fume, GGBS, Concrete Strength, Sustainable Construction, Durability, Pozzolanic Materials

1. Introduction

Concrete is widely recognized as one of the most important construction materials used in modern infrastructure. It is utilized in buildings, bridges, pavements, and numerous engineering structures due to its strength, durability, and adaptability. However, the production of ordinary Portland cement (OPC), which is the primary binder in concrete, contributes significantly to global carbon dioxide emissions. Cement manufacturing involves high energy consumption and releases considerable amounts of greenhouse gases into the atmosphere.

Due to increasing environmental concerns, researchers and engineers have focused on developing sustainable alternatives that can reduce the amount of cement used in concrete production. One of the most effective strategies involves incorporating supplementary cementitious materials (SCMs) that partially replace cement while maintaining or improving the performance of concrete.

Among these materials, silica fume and ground granulated blast furnace slag (GGBS) have gained considerable attention. Silica fume is a very fine powder obtained as a by-product during the production of silicon metal or ferrosilicon alloys. It possesses extremely small particles and high silica content, which allows it to react with calcium hydroxide in cement paste through a pozzolanic reaction. This reaction produces additional calcium silicate hydrate (C-S-H), which improves the strength and density of concrete.

GGBS is another industrial by-product produced during iron manufacturing in blast furnaces. After rapid cooling and grinding, it becomes a cementitious material that can partially replace

Portland cement in concrete mixtures. GGBS contributes to long-term strength development and improves resistance to chemical attack, sulfate exposure, and chloride penetration.

Combining silica fume with GGBS may provide a balanced performance in concrete. Silica fume contributes to early-age strength and microstructural densification, while GGBS enhances long-term durability and workability. Therefore, this research focuses on evaluating the mechanical and durability performance of concrete containing a binary blend of 10% silica fume and 10% GGBS as partial replacement of cement.

2. Research Objectives

The main objective of this study is to investigate the influence of replacing a portion of cement with silica fume and GGBS on the performance of concrete. The specific objectives include:

1. To evaluate the compressive strength of concrete containing silica fume and GGBS.
2. To analyze the effect of the replacement materials on the workability of concrete.
3. To assess durability characteristics such as permeability and resistance to environmental exposure.
4. To compare the performance of modified concrete with conventional concrete mixtures.

3. Research Significance

This study is important from environmental, engineering, and economic perspectives.

Environmental importance: Cement production is one of the major contributors to global CO_2 emissions. Using industrial by-products such as silica fume and GGBS reduces the demand for cement and helps lower environmental impacts.

Engineering significance: The addition of silica fume and GGBS improves the internal microstructure of concrete, resulting in higher compressive strength and better resistance to aggressive environments.

Economic benefits: Utilizing industrial waste materials provides an economical alternative to traditional cement usage while also addressing waste management challenges.

Scientific contribution: The study contributes to understanding the synergistic interaction between silica fume and GGBS when used together as partial cement replacements in concrete mixtures.

4. Literature Review

Previous research has demonstrated the benefits of using supplementary cementitious materials in concrete. Silica fume has been shown to significantly enhance compressive strength and reduce permeability due to its very fine particles and strong pozzolanic reactivity. Researchers have also reported improvements in the interfacial transition zone between cement paste and aggregates.

Similarly, studies on GGBS have indicated that it improves long-term strength development and enhances durability properties. Concrete containing GGBS often exhibits lower heat of hydration, making it suitable for mass concrete structures. In addition, GGBS improves resistance to sulfate attack and chloride penetration.

Several studies have investigated the combined use of silica fume and GGBS. These studies suggest that the combination of the two materials may produce a synergistic effect that enhances both early and long-term performance of concrete. However, optimal replacement percentages vary depending on mixture design, curing conditions, and environmental exposure.

5. Materials

The materials used in this experimental study include:

Ordinary Portland Cement (OPC) used as the primary binder.

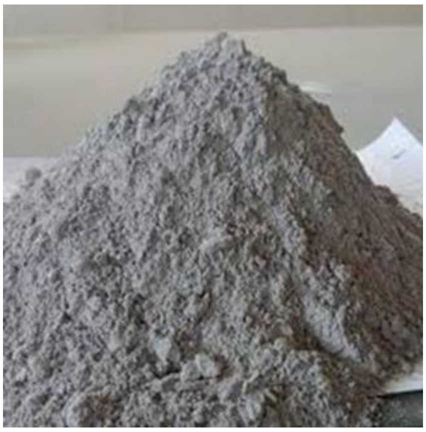
Fine aggregate (natural river sand) used to provide workability and fill voids.

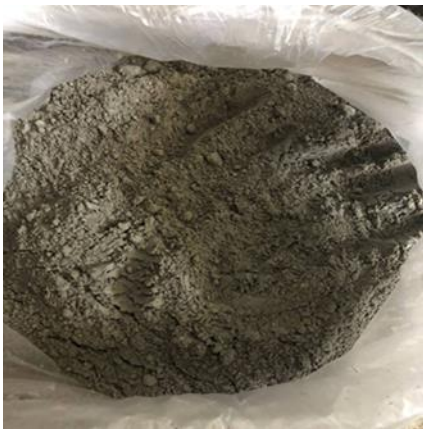
Coarse aggregate (crushed gravel) used to provide structural strength.

Silica fume used as a supplementary cementitious material at a replacement level of 10%.

Ground granulated blast furnace slag (GGBS) used as a cement replacement material at a level of 10%.Clean water used for mixing and curing the concrete specimens.

- Ordinary Portland Cement (OPC)
- Fine Aggregate (Sand)
- Coarse Aggregate (Gravel)
- Silica Fume (10%)
- GGBS (10%)
- Water





6. Experimental Methodology

Concrete specimens were prepared using both conventional and modified mixtures. The control mixture contained only ordinary Portland cement as the binder, while the modified mixture replaced 20% of cement with 10% silica fume and 10% GGBS.

The water-cement ratio was maintained at 0.40 for all mixtures. Dry materials were first mixed thoroughly to ensure uniform distribution. Water was then added gradually while mixing continued until a homogeneous mixture was obtained.

Concrete cubes with dimensions of 150 × 150 × 150 mm were cast in steel molds. After casting, the specimens were left for 24 hours before being removed from the molds and placed in water tanks for curing. Compressive strength tests were conducted after curing periods according to standard testing procedures.

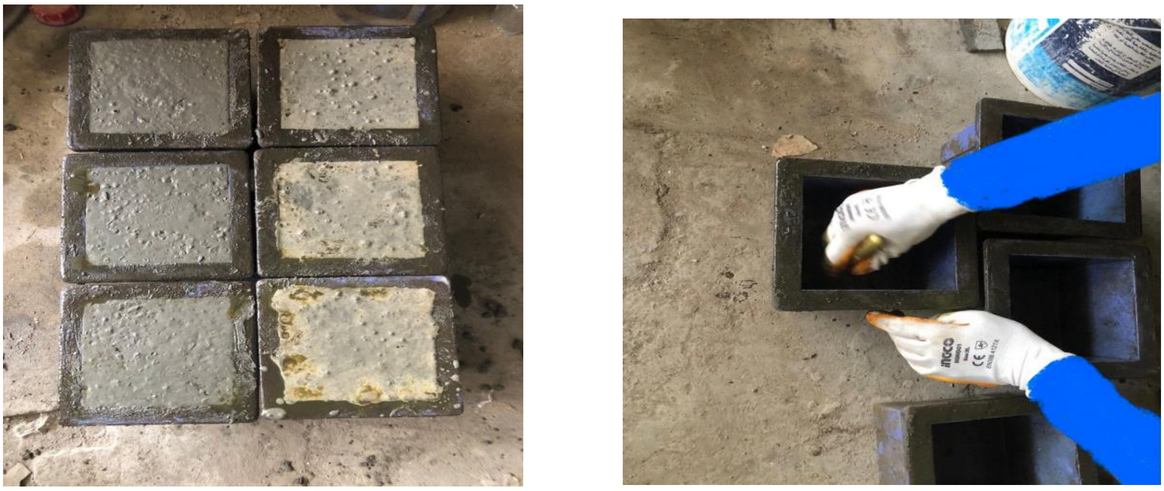


Figure 1:Cube molds(150×150×150)MM

7. Mix Design

7.1- Mix Design Proportions

Two C30 grade Mix designes (target strength 30 MPa at 28 days) were designed to produce three 150×150×150 mm cubes for each mix to achieve adequate strength and workability.

Table 1: Mix design Proportions

Material	Reference Mix	Admixed Concrete
Cement(Kg)	350 Kg/m3	7.06 Kg
Sand(Kg)	720 Kg/m3	13.25 Kg
Gravel(Kg)	1050 Kg/m3	26.5 Kg
Water(liter)	(W/C=0.4)	3.8 liter(W/C=0.4)
Silica Fume	_	0.883
GGBS	_	0.883


Figure 2: weight of aggregate

7.2-Mixing Procedure (Laboratory Batch)

The following steps were followed precisely:

Step 1: Dry Mixing

- Fine aggregate (sand) and coarse aggregate (gravel) were placed in a concrete mixer or mixing pan.
- They were mixed together for 1 minute to achieve a uniform distribution.

Step 2: Adding Binder Materials

- Cement (plus Silica Fume and GGBS for the modified mix) was added to the dry aggregates.
- All dry materials were mixed for an additional 1–2 minutes until a uniform color was achieved.

Step 3: Adding Water

- Water was measured accurately (3.8 liters for modified mix, or according to w/c ratio for control mix).
- Approximately 80% of the water was added first while mixing continued.

Step 4: Final Mixing

- The remaining 20% of water was added gradually.
- Mixing continued for another 2–3 minutes until a homogeneous concrete mixture was obtained.

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5. Casting of Specimens

- Mold Preparation: Cube molds (150 × 150 × 150 mm) were cleaned and oiled on the inner surfaces (as shown in your Figure 1).
- Filling: Fresh concrete was poured into the molds in three equal layers.
- Compaction: Each layer was compacted using a tamping rod (25–35 strokes per layer) to remove air voids.
- Vibration: A vibrating table was used for additional compaction (if available).

6. Finishing and Curing

- The top surface of each cube was leveled with a trowel.
- Molds were covered with plastic sheets to prevent moisture loss.
- After 24 hours, specimens were demolded.
- Cubes were placed in a curing tank with clean water at room temperature (≈20–25°C) for 28 days.

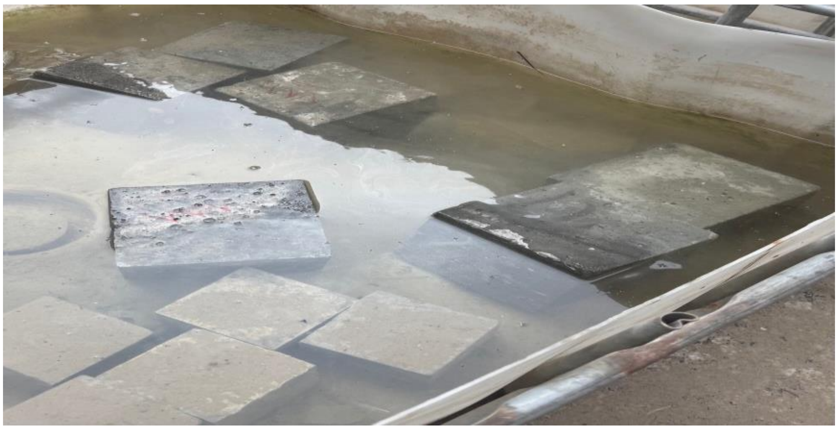


Figure 3: Curing

8. Results and Discussion

The experimental results demonstrated a clear improvement in compressive strength when silica fume and GGBS were incorporated in the concrete mixture

Concrete strength at 28 Days

Table 2: Concrete strength Test Results at 28 Days

Mix Type	Sample 1	Sample 2	Sample 3	Average (MPa)
Reference mix	40	39	40	39.7
Admixed concrete	52	56	54	54

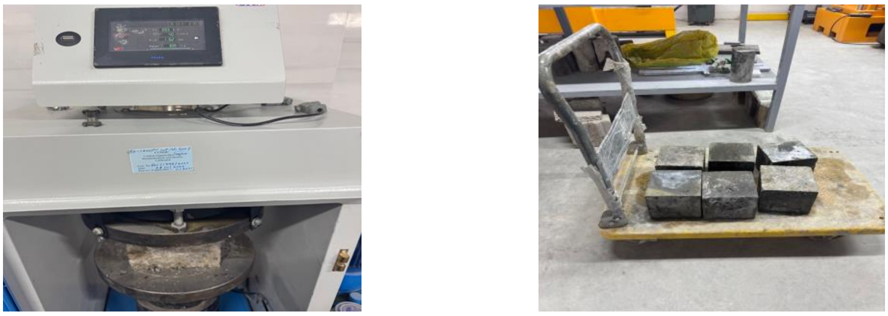
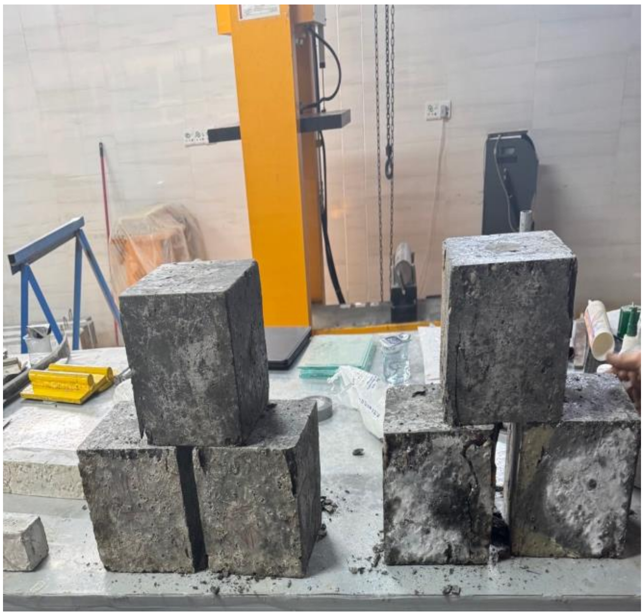
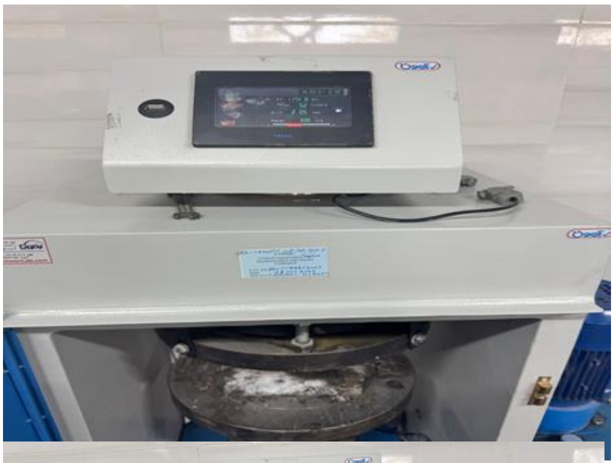


Figure 4: Compressive strength testing

The increase in compressive strength can be attributed to several mechanisms. Silica fume particles act as micro-fillers that occupy voids in the cement matrix and refine the pore structure. Additionally, the pozzolanic reaction between silica fume and calcium hydroxide generates additional C-S-H gel, which improves the overall strength of the hardened concrete.

GGBS contributes to long-term hydration reactions and enhances the density of the cement paste. The combined action of silica fume and GGBS produces a dense microstructure that improves both strength and durability of the concrete.





9. Conclusions

Based on the experimental investigation, several conclusions can be drawn. The use of silica fume and GGBS as partial replacements for cement significantly improves the compressive strength of concrete. The modified mixture containing 10% silica fume and 10% GGBS achieved higher compressive strength compared with the control mixture. The improvement in strength is mainly attributed to pozzolanic reactions and micro-filling effects that enhance the density of the concrete matrix. The modified concrete also exhibits improved durability characteristics due to reduced permeability and increased resistance to aggressive environments. Overall, partial replacement of cement with silica fume and GGBS represents an effective strategy for producing high-performance and environmentally sustainable concrete.

10. Recommendations

Future research may investigate higher replacement ratios of supplementary cementitious materials. Additional tests such as tensile strength, flexural strength, and long-term durability evaluations should also be conducted. Microstructural studies using scanning electron microscopy could further explain the hydration mechanisms occurring in blended concrete systems.

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