

Study of Mechanical Properties of M40 Grade Concrete Incorporating Ground Granulated Blast Furnace Slag and Silica Fume as Partial Replacement of Cement

Dishant Phulchand Phule¹, Dr. A. P. Wadekar², Dr. D. N. Kakade³

¹PG Student, Masters of Technology in Structural Engineering – P.E.S College of Engineering, Chhatrapati Sambhajanagar, M.S.

²Principal & Professor - P.E.S College of Engineering, Chhatrapati Sambhajanagar, M.S.

³Associate Professor and Head of Civil Engineering Department - P.E.S College of Engineering, Chhatrapati Sambhajanagar, M.S.

Abstract - Concrete is one of the most extensively used construction materials worldwide; however, the production of Ordinary Portland Cement (OPC) contributes significantly to carbon dioxide emissions and environmental degradation. The utilization of supplementary cementitious materials such as Ground Granulated Blast Furnace Slag (GGBS) and Silica Fume (SF) provides an effective approach towards sustainable concrete production. The present experimental investigation evaluates the mechanical properties of M40 grade concrete by partially replacing cement with different proportions of GGBS and Silica Fume. Seven concrete mixes were prepared, including one control mix and six ternary blended mixes containing varying percentages of GGBS (20%, 30%, and 40%) and Silica Fume (5% and 10%). The fresh and hardened properties of concrete were investigated through slump test, density measurement, compressive strength test, split tensile strength test, and flexural strength test at different curing ages. The experimental results indicate that the incorporation of GGBS and Silica Fume significantly influences the mechanical performance of concrete. The optimum performance was observed for the concrete mix containing 5% Silica Fume and 20% GGBS (M1), which achieved a maximum 28-day compressive strength of 46.65 MPa, split tensile strength of 5.58 MPa, and flexural strength of 4.02 MPa. The improvement in strength is attributed to the pozzolanic reaction of Silica Fume and the filler effect of GGBS, which results in a denser concrete microstructure. However, further increase in replacement percentages led to a reduction in mechanical strength. The study concludes that the combined utilization of GGBS and Silica Fume can effectively reduce cement consumption while improving the strength characteristics and sustainability of M40 grade concrete.

Keywords : Ground Granulated Blast Furnace Slag (GGBS), Silica Fume, M40 Concrete, Supplementary Cementitious Materials, Compressive Strength, Split Tensile Strength, Flexural Strength, Sustainable Concrete.

1. INTRODUCTION

Concrete is the most widely utilized construction material due to its excellent compressive strength, durability, availability, and adaptability in various structural applications. The rapid growth of the construction industry has resulted in a substantial increase in the consumption of Ordinary Portland Cement (OPC), which is one of the major constituents of concrete. However, the manufacturing of OPC is an energy-intensive process and is responsible for the emission of a

significant amount of carbon dioxide (CO₂), contributing to global warming and environmental degradation.

In recent years, the development of sustainable and environmentally friendly concrete has gained considerable attention. One of the effective approaches to reduce the environmental impact of concrete is the incorporation of supplementary cementitious materials (SCMs) as partial replacements of cement. These materials not only minimize the consumption of cement but also improve certain mechanical and durability properties of concrete. Among the various SCMs available, Ground Granulated Blast Furnace Slag (GGBS) and Silica Fume (SF) have emerged as promising alternatives due to their excellent pozzolanic and cementitious characteristics.

Ground Granulated Blast Furnace Slag (GGBS) is a by-product generated during the production of iron in blast furnaces. It consists primarily of calcium silicates and aluminates and possesses latent hydraulic properties. The incorporation of GGBS in concrete enhances workability, reduces the heat of hydration, improves resistance to sulphate attack, and contributes to long-term strength development. Moreover, the utilization of GGBS helps in the beneficial reuse of industrial waste and decreases the environmental burden associated with disposal.

Silica Fume (SF), also known as micro silica, is an ultra-fine powder obtained as a by-product during the manufacture of silicon metal and ferrosilicon alloys. Due to its extremely small particle size and high silicon dioxide content, Silica Fume acts as a highly reactive pozzolanic material. It reacts with calcium hydroxide produced during cement hydration and forms additional calcium silicate hydrate (C-S-H) gel, which refines the pore structure and enhances the strength and impermeability of concrete.

The combined utilization of GGBS and Silica Fume in concrete results in a ternary blended system that offers the advantages of both materials. GGBS contributes to improved workability and long-term performance, while Silica Fume enhances early-age strength through its filler effect and pozzolanic reaction. The synergistic interaction between these supplementary materials can produce concrete with superior mechanical properties and improved sustainability compared to conventional OPC concrete.

Several researchers have reported the positive influence of GGBS and Silica Fume on the performance of concrete. The replacement of cement with suitable proportions of these materials can improve compressive strength, split tensile strength, flexural strength, durability, and resistance against aggressive environmental conditions. However, the mechanical behavior of concrete depends significantly on the percentage of replacement and the combination of supplementary cementitious materials used.

Therefore, the present study investigates the mechanical performance of M40 grade concrete containing different combinations of GGBS and Silica Fume as partial replacements of cement. A total of seven concrete mixes, including one control mix and six ternary blended mixes with varying percentages of GGBS (20%, 30%, and 40%) and Silica Fume (5% and 10%), were prepared. The performance of these mixes was evaluated through workability, density, compressive strength, split tensile strength, and flexural strength tests. The objective of the study is to identify the optimum combination of GGBS and Silica Fume that provides enhanced mechanical properties while reducing the consumption of conventional cement.

2. RESEARCH GAP AND OBJECTIVES

2.1 Research Gap

The extensive use of supplementary cementitious materials such as Ground Granulated Blast Furnace Slag (GGBS) and Silica Fume (SF) has demonstrated considerable potential in improving the sustainability and performance of concrete. Several previous studies have reported enhancement in compressive strength, tensile strength, flexural strength, durability, and resistance to aggressive environmental conditions through the partial replacement of cement with these materials.

Although significant research has been carried out on the individual use of GGBS and Silica Fume, as well as their combined application in ternary blended concrete, the optimum replacement proportion is highly dependent on concrete grade, curing conditions, water-cement ratio, and mix composition. Previous investigations have mainly focused on limited combinations of supplementary cementitious materials or different grades of concrete.

A detailed experimental investigation on the mechanical behavior of M40 grade concrete incorporating different combinations of GGBS (20%, 30%, and 40%) and Silica Fume (5% and 10%) is still limited. Moreover, a comparative assessment of fresh and hardened concrete properties, including workability, density, compressive strength, split tensile strength, and flexural strength, is required to determine the most effective combination of these materials.

Therefore, the present research focuses on developing a ternary blended M40 concrete using GGBS and Silica Fume as partial replacements for Ordinary Portland Cement. The study aims to determine the optimum replacement level that provides enhanced mechanical performance while reducing cement consumption and promoting sustainable construction practices.

2.2 Objectives

The primary objectives of the present experimental investigation are:

1. To develop M40 grade concrete incorporating different combinations of Ground Granulated Blast Furnace Slag (GGBS) and Silica Fume (SF) as partial replacements of cement.
2. To evaluate the influence of GGBS and Silica Fume on the fresh properties of concrete through workability assessment.
3. To investigate the effect of varying replacement levels of GGBS and Silica Fume on the density of hardened concrete.
4. To determine the mechanical properties of ternary blended concrete by conducting:
 - Compressive Strength Test
 - Split Tensile Strength Test
 - Flexural Strength Test
5. To compare the performance of conventional M40 concrete with concrete containing different percentages of GGBS and Silica Fume.
6. To identify the optimum combination of GGBS and Silica Fume that provides maximum strength and improved concrete performance.
7. To promote the utilization of industrial by-products in concrete production for reducing cement consumption and achieving sustainable construction.

2.3 Novelty of the Present Study

The novelty of this research lies in the systematic evaluation of M40 grade ternary blended concrete containing varying proportions of GGBS and Silica Fume. The study investigates six different replacement combinations and compares their performance with conventional concrete.

Unlike many previous studies that focus on individual supplementary materials, this investigation examines the combined synergistic effect of GGBS and Silica Fume on both fresh and hardened properties of concrete. The experimental results identify an optimum blend of GGBS and Silica Fume that enhances compressive, split tensile, and flexural strength while reducing the dependence on Ordinary Portland Cement.

The findings of this research provide useful insights for the practical application of sustainable high-performance concrete in modern construction.

3. Materials and Experimental Program

3.1 Materials Used

The experimental investigation was carried out using Ordinary Portland Cement (OPC), Ground Granulated Blast Furnace Slag (GGBS), Silica Fume (SF), fine aggregate, coarse aggregate, potable water, and a chemical admixture (superplasticizer). The properties of individual materials are described below.

3.1.1 Cement

Ordinary Portland Cement (OPC) was used as the primary binding material in all concrete mixes. The physical properties of cement were evaluated according to relevant Indian Standard specifications.

Table 1. Physical Properties of Cement

Property	Value
Specific Gravity	3.15
Standard Consistency	33%
Initial Setting Time	45 minutes
Final Setting Time	320 minutes
Soundness	2 mm
28-Day Compressive Strength	55.5 MPa

3.1.2 Ground Granulated Blast Furnace Slag (GGBS)

Ground Granulated Blast Furnace Slag (GGBS) was used as a partial replacement of cement. It is a by-product obtained from the iron manufacturing industry and possesses latent hydraulic properties. The use of GGBS improves workability, reduces heat of hydration, and contributes to long-term strength development.

The specific gravity of GGBS was found to be **2.85**.

3.1.3 Silica Fume (SF)

Silica Fume was used as a highly reactive supplementary cementitious material due to its extremely fine particle size and high silica content. It enhances the microstructure of concrete through its pozzolanic reaction and filler effect.

The specific gravity of Silica Fume was found to be **2.20**.

3.1.4 Fine Aggregate

Natural river sand conforming to Zone-I was used as fine aggregate. The sand was clean and free from harmful organic impurities.

Table 2. Physical Properties of Fine Aggregate

Property	Value
Type	Natural River Sand
Zone	Zone-I
Specific Gravity	2.90
Fineness Modulus	3.25

3.1.5 Coarse Aggregate

Crushed angular coarse aggregate with a maximum size of 20 mm was used in the concrete mix.

Table 3. Physical Properties of Coarse Aggregate

Property	Value
Maximum Size	20 mm
Specific Gravity	2.74
Type	Crushed Angular Aggregate

3.1.6 Water

Potable water free from harmful substances was used for concrete mixing and curing. The quality of water satisfied the requirements of IS 456:2000.

3.1.7 Superplasticizer

A chemical admixture (superplasticizer) was incorporated to maintain adequate workability of concrete while keeping the water-cement ratio low. The dosage of superplasticizer was maintained at approximately 2% of the total cementitious material.

3.2 Concrete Mix Proportions

The M40 grade concrete mix was designed according to the guidelines of IS 10262:2009. A total of seven concrete mixes were prepared, including one control mix (M0) and six ternary blended concrete mixes containing different combinations of GGBS and Silica Fume.

Table 4. Mix Identification and Replacement Levels

Mix ID	Silica Fume (%)	GGBS (%)	Total Cement Replacement (%)
M0	0	0	0
M1	5	20	25
M2	5	30	35
M3	5	40	45
M4	10	20	30
M5	10	30	40
M6	10	40	50

Table 5. Concrete Mix Proportions (kg/m³)

Material	M0	M1	M2	M3	M4	M5	M6
Cement	350.00	288.75	250.25	211.75	269.50	231.00	192.50
Silica Fume	0.00	19.25	19.25	19.25	38.50	38.50	38.50

GGBS	0.00	77.00	115.50	154.00	77.00	115.50	154.00
Water	140.00	140.00	140.00	140.00	140.00	140.00	140.00
Fine Aggregate	895.50	875.07	873.52	871.97	871.89	870.34	868.79
Coarse Aggregate	1139.70	1113.73	1111.76	1109.78	1109.68	1107.71	1105.74
Superplasticizer	7.00	7.70	7.70	7.70	7.70	7.70	7.70

3.3 Specimen Preparation and Curing

Concrete ingredients were mixed thoroughly to obtain a homogeneous mixture. The fresh concrete was placed in moulds and compacted properly to eliminate air voids.

The following specimens were prepared for the experimental investigation:

- Cubes of size **150 mm × 150 mm × 150 mm** for compressive strength testing.
- Cylinders of size **150 mm diameter × 300 mm height** for split tensile strength testing.
- Beams of size **150 mm × 150 mm × 700 mm** for flexural strength testing.

After casting, the specimens were kept undisturbed for 24 hours and then demoulded. The specimens were cured in clean water for periods of **7 days and 28 days** before testing.

3.4 Testing Methodology

The fresh and hardened properties of concrete were evaluated through standard laboratory tests.

- **Workability Test:** Slump cone test was performed to determine the workability of fresh concrete.
- **Density Measurement:** The density of hardened concrete specimens was measured after curing.
- **Compressive Strength Test:** Conducted on cube specimens according to IS 516.
- **Split Tensile Strength Test:** Conducted on cylindrical specimens to evaluate tensile resistance.
- **Flexural Strength Test:** Conducted on beam specimens using the modulus of rupture method.

The experimental results obtained from these tests were analyzed to identify the optimum combination of GGBS and Silica Fume for producing sustainable high-strength M40 concrete.

4. Results and Discussion

The mechanical and fresh properties of M40 grade concrete containing different proportions of Ground Granulated Blast Furnace Slag (GGBS) and Silica Fume (SF) were evaluated and compared with conventional concrete (M0). The experimental program included assessment of workability, density, compressive strength, split tensile strength, and flexural strength of the developed concrete mixes.

4.1 Workability and Density

The workability and density values of all concrete mixes are presented in Table 6.

Table 6. Workability, Density and Compressive Strength of Concrete Mixes

Mix ID	Density (kg/m ³)	Slump (mm)	7-Day Compressive Strength (MPa)	28-Day Compressive Strength (MPa)
M0	2430.42	80	25.16	35.65
M1	2478.95	82	28.49	46.65
M2	2504.42	83	28.98	42.80
M3	2516.87	85	27.18	40.18
M4	2523.82	85	27.75	39.17
M5	2434.16	86	26.26	37.52
M6	2533.82	88	24.98	35.82

The slump values increased from 80 mm for conventional concrete to 88 mm for M6, indicating that the incorporation of GGBS and Silica Fume improved the workability of fresh concrete. This improvement can be attributed to the smooth texture and particle characteristics of GGBS, which reduce internal friction between aggregate particles and improve the flow characteristics of the concrete mixture.

The density of concrete generally increased with the addition of GGBS and Silica Fume due to improved particle packing and reduction of internal voids. The highest density of 2533.82 kg/m³ was observed for M6.

4.2 Compressive Strength Analysis

The variation of compressive strength with different replacement levels of GGBS and Silica Fume is shown in Figure 1.

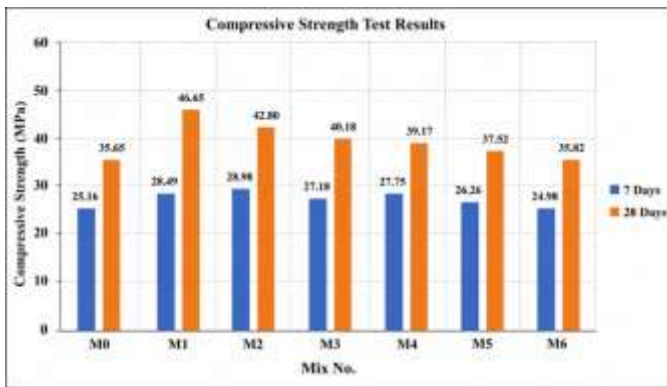


Figure 1. Variation of Compressive Strength of Concrete Mixes

The compressive strength of all ternary blended concrete mixes was found to be higher than that of the control concrete at optimum replacement levels. The M1 mix containing 5% Silica Fume and 20% GGBS achieved the highest 28-day compressive strength of 46.65 MPa, which represents approximately 30.85% improvement compared to conventional M40 concrete.

The improvement in compressive strength is mainly due to the combined pozzolanic activity of Silica Fume and GGBS. The ultra-fine Silica Fume particles fill the micro-pores and react with calcium hydroxide released during cement hydration to produce additional calcium silicate hydrate (C-S-H) gel. GGBS contributes to long-term strength enhancement and provides a denser cementitious matrix.

However, further increase in replacement levels beyond the optimum value resulted in a reduction in compressive strength because of the reduction in available cement content and slower hydration of excessive GGBS.

4.3 Split Tensile Strength Analysis

The split tensile strength results of different concrete mixes are presented in Table 7.

Table 7. Split Tensile of Concrete Mixes

Mix ID	7-Day Split Tensile Strength (MPa)	28-Day Split Tensile Strength (MPa)
M0	2.76	4.67
M1	3.25	5.58
M2	3.12	5.24
M3	2.98	5.05
M4	2.91	4.92
M5	2.84	4.81
M6	2.71	4.60

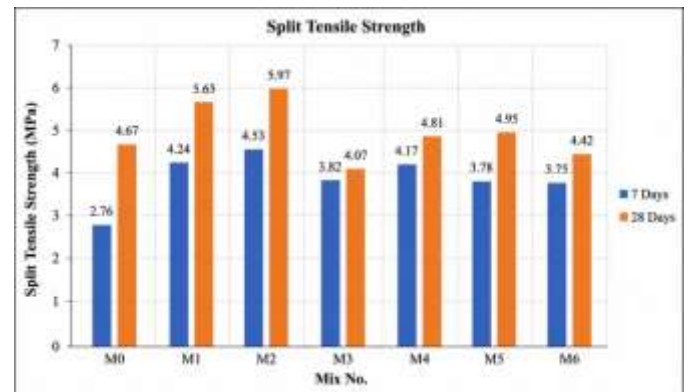


Figure 2. Split Tensile Strength of Concrete Mixes

The split tensile strength exhibited a trend similar to compressive strength. The maximum 28-day split tensile strength of 5.58 MPa was obtained for M1, showing an improvement of approximately 19.49% compared to the conventional concrete.

The improvement in tensile strength is attributed to enhanced bonding between the cement paste and aggregates due to the formation of additional C-S-H gel and a refined microstructure. The reduction in tensile strength at higher replacement percentages may be due to insufficient calcium hydroxide available for complete pozzolanic reactions and slower hydration of GGBS.

4.4 Flexural Strength Analysis

The flexural strength of concrete is an important parameter for evaluating the behavior of concrete under bending loads. The maximum 28-day flexural strength of 4.02 MPa was achieved by the M1 mix, representing an improvement of approximately 18.24% compared to the control mix.

The increase in flexural strength is due to the enhanced interfacial transition zone between the aggregate and cement matrix, improved particle packing, and the formation of additional hydration products.

As the replacement percentage increased beyond the optimum level, a gradual reduction in flexural strength was observed. This indicates that excessive replacement of cement with GGBS and Silica Fume may adversely affect the strength development of concrete.

Table 8. : Flexural Strength of Concrete Mixes

Mix ID	7-Day Flexural Strength (MPa)	28-Day Flexural Strength (MPa)
M0	2.79	3.40
M1	3.24	4.02
M2	3.11	3.88
M3	3.02	3.75
M4	2.95	3.69
M5	2.88	3.55
M6	2.76	3.38

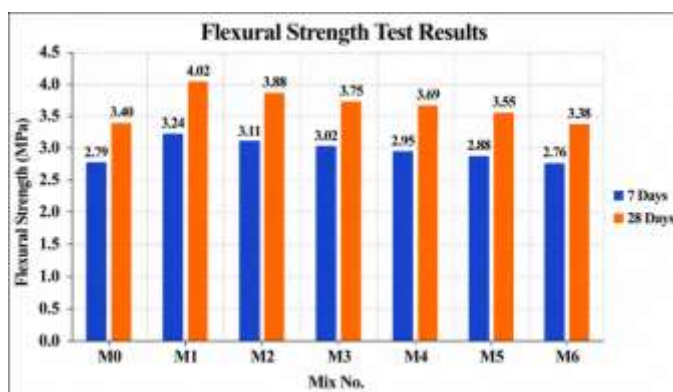


Figure 3. Flexural Strength of Concrete Mixes

4.5 Optimum Mix Selection

Based on the comprehensive analysis of workability, density, compressive strength, split tensile strength, and flexural strength, the M1 concrete mix containing **5% Silica Fume and 20% GGBS** was identified as the optimum combination.

The superior performance of M1 can be attributed to the balanced synergistic effect of GGBS and Silica Fume. GGBS enhanced workability and contributed to the development of a dense microstructure, while Silica Fume improved the microstructure through its filler effect and rapid pozzolanic reaction.

Therefore, the combination of 5% Silica Fume and 20% GGBS can be effectively utilized as a sustainable partial replacement of cement in M40 grade concrete, providing improved mechanical properties while reducing environmental impact.

5. Conclusions

Based on the experimental investigation conducted on M40 grade concrete containing different proportions of Ground Granulated Blast Furnace Slag (GGBS) and Silica Fume (SF) as partial replacements of cement, the following conclusions can be drawn:

1. The incorporation of GGBS and Silica Fume significantly influenced the fresh and mechanical properties of M40 grade concrete.
2. The workability of concrete increased with increasing replacement percentages of GGBS and Silica Fume. The maximum slump value of 88 mm was obtained for the M6 mix, indicating improved flow characteristics of ternary blended concrete.
3. The density of concrete generally increased with the incorporation of GGBS and Silica Fume due to better particle packing and reduction of internal voids. The highest density of 2533.82 kg/m³ was observed for the M6 mix.
4. The compressive strength of ternary blended concrete was enhanced up to an optimum replacement level. The maximum 28-day compressive strength of 46.65 MPa was achieved by the M1 mix containing 5% Silica Fume and 20% GGBS, which exhibited approximately 30.85% higher strength than conventional concrete.
5. The split tensile strength also followed a similar trend, where the M1 mix achieved the highest 28-day

split tensile strength of 5.58 MPa, showing an improvement of approximately 19.49% over the control mix.

6. The maximum 28-day flexural strength of 4.02 MPa was obtained for the M1 mix, representing an improvement of approximately 18.24% compared with conventional M40 concrete.
7. The improvement in mechanical properties is attributed to the combined effect of Silica Fume and GGBS. The ultra-fine Silica Fume particles fill the micro-pores and promote secondary C-S-H gel formation, while GGBS contributes to a denser and more durable cementitious matrix.
8. Higher replacement levels of GGBS and Silica Fume beyond the optimum percentage resulted in a reduction in strength due to a decrease in effective cement content and slower hydration reactions.
9. The optimum combination identified in the present investigation was **5% Silica Fume and 20% GGBS (M1)**, which provided the best balance between workability and mechanical performance.
10. The partial replacement of cement with GGBS and Silica Fume provides a sustainable approach for concrete production by reducing cement consumption, utilizing industrial by-products, and decreasing the environmental impact associated with cement manufacturing.

Overall, the study demonstrates that the combined utilization of GGBS and Silica Fume can effectively produce sustainable high-performance M40 concrete with improved mechanical characteristics.

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