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Innovative Mix Design and Performance Evaluation of M70–M90 Grade High-Strength Concrete Utilizing GGBS and Silica Fume

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Abstract

High-strength concrete (HSC) generally requires a higher cement content, which increases the heat of hydration, raising the risk of thermal cracking and ultimately reducing structural performance. Moreover, using more ordinary Portland cement (OPC) leads to higher CO_2 emissions, posing environmental concerns. To address these issues while maintaining durability, ongoing research is exploring the use of supplementary cementitious materials (SCMs) such as ground granulated blast furnace slag (GGBS) and silica fume (SF).

This study focuses on evaluating the strength characteristics of HSC incorporating GGBS and SF. In the experimental program, GGBS and SF were used to partially replace OPC in proportions ranging from 30% to 50%, with the aim of producing M70 to M90 grade concrete. Tests included slump flow measurements, compressive strength at 3, 7, and 28 days, and ultrasonic pulse velocity (UPV) assessments at 28 days.

The results indicated that both GGBS- and SF-based HSC achieved the target high strength, with SF-based mixes demonstrating superior strength performance compared to those incorporating GGBS.

Key words: **High Strength Concrete,GGBS,SF, compressive strength & UPV**

Introduction

Concrete is one of the most widely used construction materials across the globe, valued for its durability, versatility, and ease of use. It can be conveniently produced on-site for high-rise structures, easily transported to required locations, and cast into a variety of shapes and sizes using molds [1]. High-strength concrete (HSC), however, requires a greater amount of binder. Increasing the cement content not only raises material costs but also elevates the heat of hydration and the risk of early-age shrinkage cracking [2].

These challenges can be addressed by incorporating supplementary cementitious materials (SCMs) such as fly ash, ground granulated blast furnace slag (GGBS), silica fume (SF), and rice husk ash (RHA) [3]. GGBS and SF, in particular, serve as effective partial replacements for ordinary Portland cement, enhancing the compressive strength of HSC. Studies have shown that mixes containing GGBS and SF achieve higher strength compared to conventional concrete [4]. Furthermore, the inclusion of these materials not only improves slump flow and early-age strength but also leads to the formation of a denser, less porous calcium silicate hydrate (C–S–H) gel layer around cement particles [5].

The objective of this study was to develop high-strength concrete (HSC) incorporating ground granulated blast furnace slag (GGBS) and silica fume (SF) as partial cement replacements at varying levels from 30% to 50%. The investigation focused on evaluating the fresh properties of the mixes through slump flow tests, assessing compressive strength at 3, 7, and 28 days of curing, and measuring the ultrasonic pulse velocity (UPV) of the concrete at 28 days.

Experimental Work

In this study, Ordinary Portland Cement (OPC) of grade 53 was used, with ground granulated blast furnace slag (GGBS) and silica fume (SF) incorporated as supplementary cementitious materials (SCMs) at varying replacement levels. Coarse aggregates with a maximum size of 10 mm and natural river sand in a 67:33 ratio were used. The specific gravities of cement, GGBS, SF, 10 mm coarse aggregate, and river sand were 3.15, 2.90, 2.20, 2.60, and 2.60, respectively.

High-strength concrete (HSC) of grades M70 to M90 was designed in accordance with IS 456:2000 [6] and IS 10262:2019 [7]. The replacement levels of GGBS and SF ranged from 30% to 50%. A superplasticizer dosage of 0.8% by weight of binder was used consistently across all mixes. The proportions of coarse and fine aggregates were maintained at 63% and 37%, respectively.

Workability was assessed using the slump test, while compressive strength tests were carried out on cube specimens at 3, 7, and 28 days of curing in accordance with IS 516:2021. The ultrasonic pulse velocity (UPV) test was performed at 28 days following BIS 13311-92 (Part I). The detailed mix proportions for GGBS- and SF-blended HSC are presented in the following tables.

Table 1. GGBS blended HSC mix proportions

Mix	Cementitious (Kg/m^3)	Cement (Kg/m^3)	GGBS (Kg/m^3)	Water (litre/m^3)	w/cm	10mm (Kg/m^3)	Sand (Kg/m^3)	SP (%)
C400GGBS230	630	400	230	190.4	0.33	978.54	574.69	0.8
C770GGBS330	1100	770	330	190.4	0.19	723.89	425.20	0.8
C770GGBS440	1210	770	440	190.4	0.17	660.11	387.7	0.8
C770GGBS630	1400	770	630	190.4	0.15	550.37	323.23	0.8
C770GGBS770	1540	770	770	190.4	0.14	468.47	275.13	0,8
C900GGBS390	1290	900	390	190.4	0.16	620.8	364.68	0.8
C900GGBS510	1410	900	510	190.4	0.15	550.36	323.23	0.8

Table2. Parameters of GGBS blended HSC mix proportions

Mix	Cementitious (Kg/m^3)	Cement (Kg/m^3)	GGBS (Kg/m^3)	w/cm	GGBS/Cement (GGBS/C)	%GGBS
C400GGBS230	630	400	230	0.33	0.6	35
C770GGBS330	1100	770	330	0.19	0.4	30
C770GGBS440	1210	770	440	0.17	0.6	35
C770GGBS630	1400	770	630	0.15	0.8	45
C770GGBS770	1540	770	770	0.14	1	50
C900GGBS390	1290	900	390	0.16	0.4	30

C900GGBS510	1410	900	510	0.15	0.6	35

Table3.SF blended HSC mix proportions

Mix	Cementitious (Kg/m^3)	Cement (Kg/m^3)	SF (Kg/m^3)	Water (litre/m^3)	w/cm	10mm (Kg/m^3)	Sand (Kg/m^3)	SP (%)
C400SF230	630	400	230	190.4	0.33	938.08	550.94	0.8
C770SF330	1100	770	330	190.4	0.19	664.7	390.38	0.8
C770SF440	1210	770	440	190.4	0.17	581.02	341.41	0.8
C770SF630	1400	770	630	190.4	0.15	437.35	256.85	0.8
C770SF770	1540	770	770	190.4	0.14	331.36	194.62	0,8
C900SF390	1290	900	390	190.4	0.16	549.22	332.56	0.8
C900SF510	1410	900	510	190.4	0.15	458.31	269.16	0.8

Table4. Parameters of SF blended HSC mix proportions

Mix	Cementitious (Kg/m^3)	Cement (Kg/m^3)	SF (Kg/m^3)	w/cm	SF/Cement (SF/C)	%SF
C400SF230	630	400	230	0.33	0.6	35
C770SF330	1100	770	330	0.19	0.4	30
C770SF440	1210	770	440	0.17	0.6	35
C770SF630	1400	770	630	0.15	0.8	45
C770SF770	1540	770	770	0.14	1	50
C900SF390	1290	900	390	0.16	0.4	30
C900SF510	1410	900	510	0.15	0.6	35

Results and discussion

This section presents and discusses the experimental results. Slump flow measurements were conducted for all HSC mixes, along with compressive strength tests at 3, 7, and 28 days of curing. Ultrasonic pulse velocity (UPV) was measured at 28 days.

Table 5 presents the slump flow results for GGBS-blended HSC mixes. The data indicate that increasing the proportion of GGBS leads to a reduction in slump flow values. Similarly, Table 6 shows the slump flow results for SF-blended HSC mixes, where a higher replacement level of SF also resulted in lower slump flow values.

However, it was observed that, for comparable replacement levels, SF-blended HSC mixes exhibited higher slump flow than their GGBS-blended counterparts.

Table5. Slump flow values of GGBS blended HSC mixes

Mix	Cementitious (Kg/m^3)	Cement (Kg/m^3)	GGBS (Kg/m^3)	GGBS/Cement (GGBS/C)	%GGBS	Slump flow (mm)
C400GGBS230	630	400	230	0.6	35	551
C770GGBS330	1100	770	330	0.4	30	590
C770GGBS440	1210	770	440	0.6	35	628
C770GGBS630	1400	770	630	0.8	45	619
C770GGBS770	1540	770	770	1	50	572
C900GGBS390	1290	900	390	0.4	30	662
C900GGBS510	1410	900	510	0.6	35	648

Table 6. Slump flow values of SF blended HSC mixes

Mix	Cementitious (Kg/m^3)	Cement (Kg/m^3)	SF (Kg/m^3)	SF/Cement (SF/C)	%SF	Slump flow (mm)
C400SF230	630	400	230	0.6	35	563
C770SF330	1100	770	330	0.4	30	609
C770SF440	1210	770	440	0.6	35	636
C770SF630	1400	770	630	0.8	45	624
C770SF770	1540	770	770	1	50	593
C900SF390	1290	900	390	0.4	30	670
C900SF510	1410	900	510	0.6	35	654

Table 7 and Table 8 shows the strength properties of GGBS based and SF based HSC mixes at different curing periods.

Table7. Compressive strength of GGBS based HSC mixes

Mix	GGBS/Cement (GGBS/C)	%GGBS	Compressive strength(MPa)			Grade
			3days	7days	28days	
C400GGBS230	0.6	35	64	73	78	M70
C770GGBS330	0.4	30	73	81	85	M80
C770GGBS440	0.6	35	73	83	89	M80

C770GGBS630	0.8	45	72	82	84	M70
C770GGBS770	1	50	65	76	79	M70
C900GGBS390	0.4	30	74	89	92	M80
C900GGBS510	0.6	35	66	77	82	M70

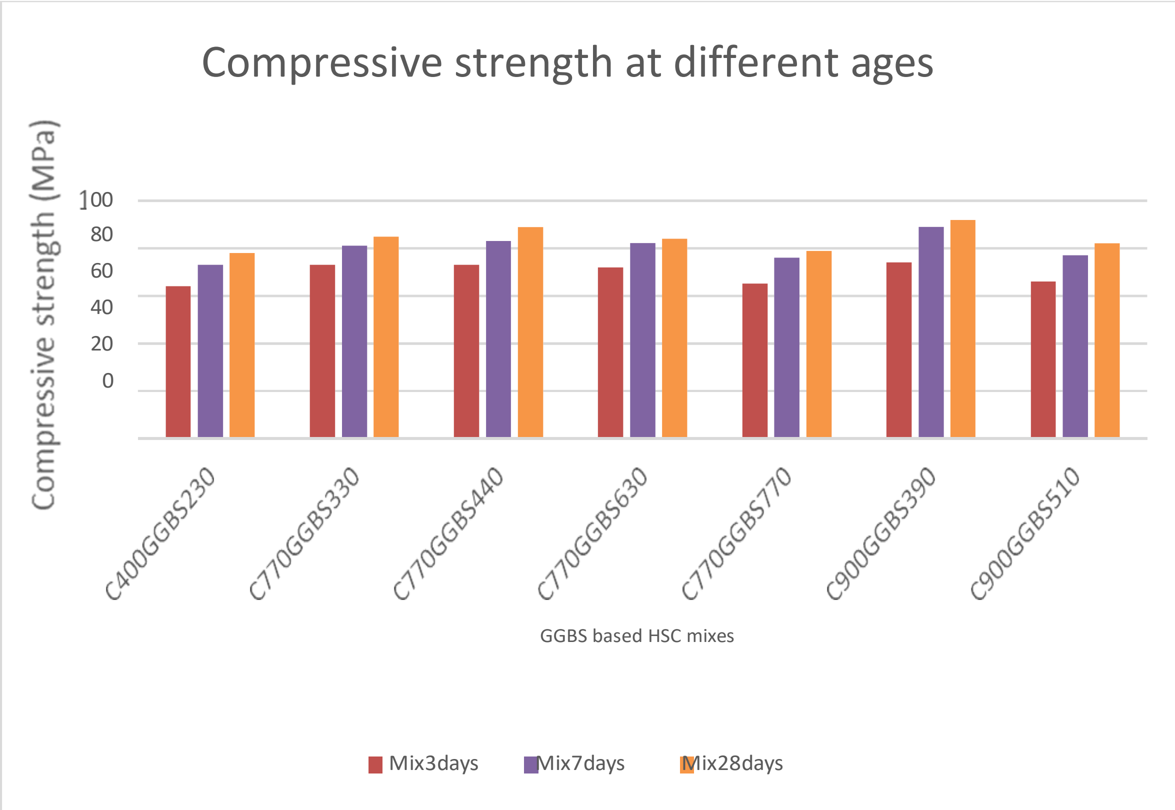

Fig.1. Compressive strength of GGBS based HSC at different ages

Table8. Compressive strength of SF based HSC mixes

Mix	/Cement (SF/C)	%SF	Compressive strength(MPa)			Grade
			3days	7days	28days	
C400SF230	0.6	35	70	80	85	M80
C770SF330	0.4	30	76	85	92	M80
C770SF440	0.6	35	79	89	96	M90
C770SF630	0.8	45	74	81	86	M80
C770SF770	1	50	71	78	83	M70
C900SF390	0.4	30	80	94	98	M90
C900SF510	0.6	35	66	77	82	M70

Compressive strength (MPa)

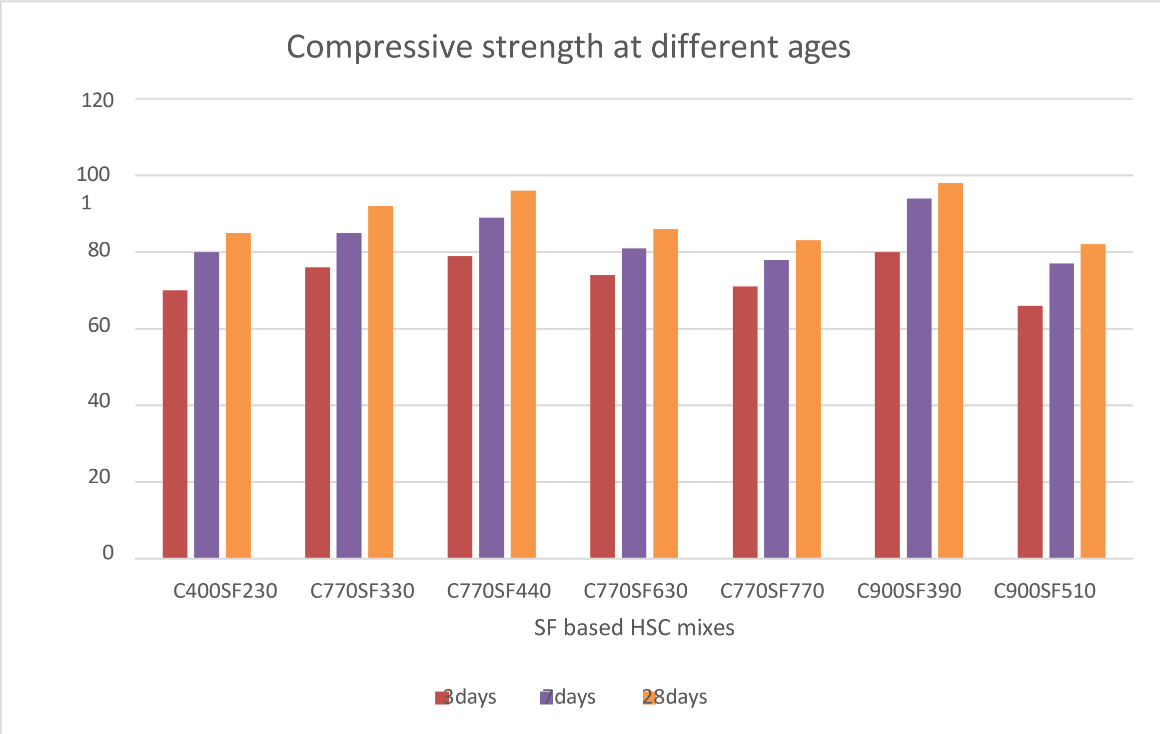

Fig.2.: Compressive strength of SF based HSC at different ages

Fig.3. Compressive strength testing of Cubes

Tables 7 and 8 present the compressive strength values for the GGBS- and SF-based HSC mixes at 3, 7, and 28 days of curing, with corresponding grades as per IS 456:2000.

For GGBS-blended HSC, all mixes achieved target strengths corresponding to M70 or M80 grades after 28 days. Notably, mixes C770GGBS330, C770GGBS440, and C900GGBS390 achieved M80-grade strength, while the remaining mixes, such as C400GGBS230, C770GGBS630, C770GGBS770, and C900GGBS510, attained

M70-grade strength.

For SF-blended HSC, the performance was comparatively higher. Mixes C770SF440 and C900SF390 achieved M90-grade strength after 28 days, while C400SF230, C770SF330, and C770SF630 reached M80-grade strength. Mixes with the highest SF replacement (C770SF770 and C900SF510) achieved M70-grade strength.

The comparison between GGBS and SF mixes clearly indicates that SF-blended HSC outperformed GGBS-blended HSC at similar replacement levels, particularly in terms of 28-day compressive strength. This superior performance can be attributed to SF's high pozzolanic reactivity, which accelerates the formation of additional calcium silicate hydrate (C–S–H) gel, leading to a denser microstructure and improved strength development. Table 9 shows the ultra-pulse velocity (UPV) values of GGBS based HSC mixes after 28 days of curing.

Table 9.UPV of GGBS based HSC mixes after 28 days of curing

Mix	**UPV(m/s)**
C400GGBS230	4569
C770GGBS330	4659
C770GGBS440	4781
C770GGBS630	4543
C770GGBS770	4572
C900GGBS390	4789
C900GGBS510	4651

Fig.4. UPV testing on Cubes

Table 9 presents the UPV values of GGBS-blended HSC mixes measured after 28 days of curing. All mixes recorded values above 4500 m/s, which, according to IS 13311 (Part 1), corresponds to *excellent* concrete quality. The highest UPV value among the GGBS mixes was observed for C900GGBS390 (4789 m/s), indicating a very dense internal structure, while the lowest value was recorded for C770GGBS630 (4543 m/s). The variation in UPV values is likely due to differences in microstructural densification, which depends on both binder content and replacement levels.

Table10 shows the ultra-pulsevelocity (UPV) values of SF based HSC mixes after28 days of curing.

Table10.UPV of SF based HSC mixes after 28 days of curing

Mix	**UPV(m/s)**
C400SF230	4806
C770SF330	4898
C770SF440	4901
C770SF630	4823
C770SF770	4798
C900SF390	4916
C900SF510	4752

Table 10 shows the UPV results for SF-blended HSC mixes. Similar to the GGBS mixes, all SF mixes achieved UPV values above 4500 m/s, indicating excellent quality concrete. The highest value was recorded for C900SF390 (4916 m/s), closely followed by C770SF440 (4901 m/s) and C770SF330 (4898 m/s). These high values reflect the superior packing density and refined pore structure contributed by the highly reactive silica fume, which enhances the formation of dense calcium silicate hydrate (C–S–H) gel.

When comparing the two types of SCMs, SF-blended mixes consistently achieved slightly higher UPV values than GGBS-blended mixes at equivalent replacement levels. This suggests that SF not only contributes to higher compressive strength but also improves the homogeneity and density of the concrete matrix, leading to more effective ultrasonic wave propagation.

Conclusions

Based on the findings of this investigation, the following conclusions can be drawn:

1. **Effect of GGBS on Workability** – Increasing the replacement level of GGBS in HSC mixes led to a reduction in slump flow values, indicating a decrease in workability. This can be attributed to the finer particle size and higher water demand of GGBS compared to OPC.
2. **Effect of SF on Workability** – Similarly, higher replacement levels of SF resulted in reduced slump flow values. However, due to the spherical particle shape of silica fume, the reduction in workability was less pronounced than in GGBS mixes.
3. **Comparison of GGBS and SF in Workability** – At corresponding replacement levels, SF-blended mixes consistently exhibited higher slump flow values than GGBS-blended mixes, suggesting better flowability and ease of placement when using SF.
4. **Strength Performance of GGBS Mixes** – After 28 days of curing, GGBS-blended HSC mixes achieved target compressive strengths corresponding to M70 and M80 grades, demonstrating that high-performance concrete can be produced with partial replacement of cement by GGBS.
5. **Strength Performance of SF Mixes** – SF-blended HSC mixes achieved M70, M80, and M90 grades after 28 days, indicating superior strength development compared to GGBS mixes, particularly at moderate replacement levels.
6. **Strength Comparison** – Across all equivalent replacement levels, SF-blended mixes achieved higher compressive strengths than GGBS-blended mixes. This improvement is likely due to the higher pozzolanic reactivity of SF, which enhances microstructural densification.
7. **UPV of GGBS Mixes** – All GGBS-based HSC mixes recorded ultrasonic pulse velocity (UPV) values above 4500 m/s, classifying them as *excellent quality concrete* according to IS 13311 (Part 1).

833

8. **UPV of SF Mixes** – All SF-based HSC mixes also attained UPV values above 4500 m/s, confirming excellent concrete quality.
9. **UPV Comparison** – At similar replacement levels, SF-blended mixes showed slightly higher UPV values than GGBS-blended mixes, indicating a denser and more homogeneous internal structure that facilitates ultrasonic wave transmission.

Overall, the study confirms that both GGBS and SF can be effectively used as supplementary cementitious materials in the production of sustainable high-strength concrete, with SF delivering marginally better performance in terms of both strength and microstructural quality.

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834