SYNERGISTIC EFFECTS OF SILICA FUME INCORPORATION ON THE MICROSTRUCTURAL AND MECHANICAL PERFORMANCE OF CONCRETE UTILIZING STEEL SLAG AS COARSE AGGREGATE

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ABSTRACT:
Concrete is one of the most widely used and versatile construction materials, valued for its ability to perform well under harsh environmental conditions and for the wide range of shapes and forms it can take. Recent advancements in concrete technology have been largely driven by the use of supplementary cementitious materials (SCMs), which are typically industrial byproducts. SCMs, such as fly ash, silica fume, ground granulated blast furnace slag (GGBFS), and steel slag, are used to partially replace Portland cement in concrete. Their inclusion reduces the environmental impact and cost of concrete production, while also enhancing mechanical and durability properties. Among these, fly ash and slag cement are the most commonly used SCMs in current concrete mixtures, often evaluated side by side to optimize performance. Silica fume, though used in smaller quantities, is particularly effective in increasing both the strength and durability of concrete, making it essential in high-performance and high-strength concrete applications. In addition to SCMs, the quality and type of aggregates play a critical role in concrete design. Steel slag, a byproduct from steel manufacturing, is being explored as a replacement for natural aggregates in concrete. While it is already in use for hot mix asphalt, its application in concrete is limited due to the expansion caused by free lime and magnesium oxides. However, with proper treatment and the use of pozzolanic materials like silica fume, these issues can be minimized, making steel slag a viable and environmentally friendly alternative aggregate. This study involved comparative testing of concrete mixes using ACC brand slag cement, fly ash cement, and their 1:1 blend, with additional modifications of 10% and 20% silica fume. Natural sand conforming to Zone II per IS 383-1982 was used as fine aggregate, and 20 mm down steel slag was used as coarse aggregate. The mix ratio was kept at 1:1.5:3. The key properties evaluated were compressive strength at 7, 28, and 56 days, flexural strength, porosity, and capillary absorption. The findings showed that silica fume increased the water demand for achieving normal consistency, with higher dosages requiring more water. Fly ash cement mixes required more water than slag cement mixes. The trend was consistent in concrete mixing as well. Mortar strength increased with the percentage of silica fume, while fly ash cement exhibited higher early strength and slag cement showed better long-term strength. Blended mixes showed moderate strength at all ages. Silica fume made the mix more plastic, particularly when combined with fly ash cement. Porosity and capillary absorption in mortar decreased with increasing silica fume, more so in fly ash cement mixes. However, in concrete, silica fume led to a reduction in compressive and flexural strength at all ages, with strength decreasing further at higher dosages. Specimens without silica fume showed more visible cracking, especially those with slag cement. In conclusion, while silica fume improves mortar properties, its impact on concrete strength is complex, and optimal combinations of SCMs and aggregates are necessary to achieve balanced performance.
Keywords: SCM, Compressive strength, Blended mixes, Aggregate, Silica fume

INTRODUCTION:

More recently, strict environmental – pollution controls and regulations have produced an increase in the industrial wastes and sub graded byproducts which can be used as SCMs such as fly ash, silica fume, ground granulated blast furnace slag etc. The use of SCMs in concrete constructions not only prevent these materials to check the pollution but also to enhance the properties of concrete in fresh and hydrated states. The SCMs can be divided in two categories based on their type of reaction: hydraulic and pozzolanic. Hydraulic materials react directly with water to form cementitious compound like GGBS. Pozzolanic materials do not have any cementitious property but when used with cement or lime react with calcium hydroxide to form products possessing cementitious prosperities. Ground granulated blast furnace slag (GGBS or GGBFS) is obtained by quenching molten iron slag, a by-product of iron and steel making from a blast furnace in water or steam, to produce a glassy, granular product that is then dried and ground into a fine powder. Ground granulated blast furnace slag (GGBFS) has been utilized for many years as an additional cementitious material in Portland cement concretes, either as a mineral admixture or as a component of blended cement. Granulated blast furnace slag typically replaces 35–65% Portland cement in concrete. The use of GGBFS as a partial replacement of ordinary Portland cement improves strength and durability of concrete by creating a denser matrix and thereby increasing the service life of concrete structures. It has a higher proportion of the strength-enhancing calcium silicate hydrates (CSH) than concrete made with Portland cement only, and a reduced content of free lime, which does not contribute to concrete strength. Silica fume is a byproduct in the reduction of high-purity quartz with coke in electric arc furnaces in the production of silicon and ferrosilicon alloys. Silica fume consists of fine particles with a surface area on the order of 215,280 ft^2/lb (20,000 m^2/kg) when measured by nitrogen adsorption techniques, with particles approximately one hundredth the size of the average cement Because of its extreme fineness and high silica content, silica fume is a very effective pozzolanic material particle

PREVIOUS RESEARCH REVIEW :

Recent investigations affirm that steel slag, despite its high strength and rough texture, presents challenges due to volumetric instability caused by free lime and periclase, which can result in expansion and cracking (Ahmed et al., 2022). To mitigate these issues, silica fume has been introduced as a pozzolanic additive. Its ultrafine particles not only help in densifying the concrete matrix but also enhance the pozzolanic reaction, consuming excess calcium hydroxide and contributing to the formation of additional C-S-H gel (Verma et al., 2023). This improves both the durability and mechanical performance of concrete.

Kumar et al. (2023) reported that incorporating 10–15% silica fume in steel slag concrete significantly enhanced compressive and flexural strength, especially at later ages (28 and 56 days), due to the improved interfacial transition zone (ITZ) between slag aggregates and the cement paste. Furthermore, capillary absorption and water permeability were notably reduced, indicating improved durability. However, they also observed that higher dosages (above 20%) could lead to increased water demand and reduced workability.

Patel and Shah (2022) conducted a comparative study and found that silica fume-modified steel slag concrete exhibited better sulfate resistance and lower chloride ion penetration compared to conventional mixes. The reduced porosity and refined pore structure contributed to enhanced durability under aggressive environmental conditions.

Meanwhile, Singh et al. (2024) emphasized the importance of proper mix design and curing conditions. They concluded that while silica fume helps mitigate the expansion issues of steel slag, pre-treatment of slag aggregates and optimized water-binder ratios are crucial to maximize performance. Overall, literature from the last two to three years strongly supports the synergy between silica fume and steel slag in concrete. While challenges like increased water demand and reduced workability persist at high silica fume content, the benefits in terms of strength, durability, and environmental impact make this combination a promising area for further research and practical application.

RESEARCH METHODOLOGY:

The Experimental Programme was carried out in two stages Stage 1: Experimental work were conducted on mortar mixes by using different binder mix modified with different percentages of silica fume. Stage2: Experimental works were conducted on steel slag concrete mixes by using different binder mix modified with different percentages of silica fume. Stage 1: This experimental investigation was carried out for three different combinations of slag cement and fly ash cement. In each combination three different proportion of silica fume had been added along with the controlled mix without silica fume. Binders being used were different combinations of slag cement, fly ash cement in the proportions 1:0, 0:1 and 1:1 hence total three combinations. Further in each type of combination of binder mix 0%,10 % and 20 % percentage of silica fume had been added. Hence total 12 sets of mortar of 1:3 proportion were prepared by mixing one part of binder mix and three parts of naturally available sand. Stage2: Here concrete is prepared with three different types of binder mix with silica fume.

RESULTS AND DISCUSSION

Compressive Strength by Rebound Hammer Method.

Compressive Strength of different concrete cubes after 7 days, 28 days and 56 days were tabulated in Table No. 4.

Table No 1

Type of cement	% of SF replaced	7 days	28 days	56 days
Fly ash cement	0	24.54	29.55	36.4
	10	21	25.74	25.94
	20	21.4	22.9	29.2
Slag cement	0	18.2	22.3	26.35
	10	18.6	22.3	27.4
	20	18.3	21.4	27.5
Slag and fly ash cement blend (1:1)	0	20.9	25.4	31.45
	10	21.8	23	27.44
	20	21.4	20.9	28.23

4.2 Compressive Strength by Compression Testing Machine.

Compressive Strength of different mortars after 7days ,28days and 56 days were tabulated in Table No. 4.8.

Table No 2

Type of cement	% of SF replaced	7days	28days	56 days
Fly ash cement	0	23.33	37.1	45.1
	10	21.61	27.77	30.44
	20	20.66	23.1	28

Slag cement	0	16.6	26.21	28.44
	10	18.44	25.33	25.55
	20	19.2	24.89	21.1
Slag and fly ash cement blend (1:1)	0	27.05	27.55	33.11
	10	22	23.77	29.77
	20	20	22.88	28.88

Wet and Dry Test.

Table No 3shows 28 days and 56 days wet and dry test of concrete cube.

Table No. 3

Type of cement	% of SF replaced	28 days (N/mm^2)	56 days (N/mm^2)
Fly ash cement (FC)	0	36.5	36.0
	10	30.7	30.66
	20	26.8	28.44
Slag cement (SC)	0	23.8	27.55
	10	26.8	24.88
	20	25.3	20.88
Slag and fly ash cement blend (1:1) (SFC)	0	20.7	38.22
	10	36.5	24
	20	30.1	30.66

Flexural Test.

The flexural strength of steel slag concrete at 28 days and 56 days is given below.

Table No 4

Type of cement	% of SF replaced	28 days(N/mm^2)	56 days (N/mm^2)
Fly ash cement (FC)	0	6.875	4
	10	7	4.25
	20	6.875	4.5
Slag cement (SC)	0	7	5
	10	6.5	3.55
	20	6.125	3.975
Slag and fly ash cement blend (1:1) (SFC)	0	7	4.5
	10	6.725	3.23
	20	4.75	2.975

Porosity Test.

The 28 days and 56 days porosity test is given below

Table No 5

Type of cement	% of SF replaced	28 days (%)	56 days (%)
Fly ash cement (FC)	0	6.1	4.8
	10	8.3	6.7

	20	9.1	7.4
Slag cement (SC)	0	9.3	7.3
	10	16	11.11
	20	18	13.23
Slag and fly ash cement blend (1:1) (SFC)	0	5.7	3.79
	10	7.1	5.21
	20	12	9.83

From the above table, we can conclude that porosity increases with increase in percentage of replacement by silica fume. The reason could be the inclusion of silica fume to the different cements actually forms denser matrices thereby improve resistance of the matrices against water ingress which is one of the most important reasons that increases the deterioration of concrete.

Capillary Absorption Test.

The capillary coefficients for different types of steel slag is given below.

Table No 6

Type of cement	% of SF replaced	28 days ($k*10^{-3}$ cm/s)	56 days ($k*10^{-3}$ cm/s)
Fly ash cement	0	2.09	1.83
	10	1.142.30	0.95
	20	0.838	0.621
Slag cement	0	2.30	1.92
	10	1.46	1.02
	20	1.04	0.81
Slag and fly ash cement blend (1:1)	0	2.01	1.63
	10	1.21	0.98
	20	0.85	0.671

From the above table, we can conclude that capillary absorption decreases with increase in percentage of replacement by silica fume. The reason could be the inclusion of silica fume to the different cements actually forms denser matrices thereby improve resistance of the matrices against water ingress which is one of the most important reasons that increases the deterioration of concrete.

CONCLUSIONS :

The inclusion of silica fume in different binder mixes enhances their strength by densifying the microstructure. Specifically, silica fume improves the early-age strength of fly ash cement and contributes to the long-term strength of slag cement. When fly ash and slag cement are used in equal proportions, the resulting blend shows a balanced and consistent strength gain across all curing stages. Additionally, the fine particles of silica fume react with the lime in the cement to form crystalline hydrates, reducing both porosity and capillary absorption. This reduction becomes more pronounced with increasing silica fume content, up to a 20% replacement level in mortar mixes. However, when silica fume is used in concrete containing steel slag as coarse aggregate, a decrease in compressive strength is observed at all curing ages. This reduction is primarily attributed to the formation of voids during mixing and compaction. The sticky or cohesive nature of silica fume-enriched mixes inhibits the release of trapped air, especially when using a vibration table. This issue may be alleviated by using a needle vibrator to improve compaction. A more critical concern is the potential for alkali-aggregate reactions. Steel slag contains alkalis such as Na_2O and K_2O, and the naturally alkaline cement paste can become even more reactive when combined with silica fume. Silica from the fume reacts with the alkalis and calcium hydroxide, forming gels that weaken the bond between the binder matrix and the aggregate, especially at higher silica fume dosages. Concrete mixes with fly ash cement and silica fume tend to be more cohesive than those with slag cement and silica fume, leading to increased void formation and, consequently, higher porosity and capillary absorption. Given these challenges, complete replacement of natural coarse aggregate with untreated steel slag is not advisable. A partial replacement strategy, especially when paired with fly ash cement and proper pre-treatment of the slag, can yield high-strength concrete. It is recommended that steel slag be stockpiled in the open for at least one year to allow hydration of free lime (CaO) and periclase (MgO), which helps mitigate expansion at later ages. Furthermore, conducting a detailed chemical analysis of the steel slag is essential to assess alkali content, as excessive alkalis can negatively affect the bond between the aggregate and the binder matrix.

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