Synergistic Effects of Silica Fume and Steel Slag and Steel Slag in Advanced Concrete Composites

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Abstract
Concrete is highly versatile, capable of withstanding harsh environments and achieving inspirational forms. Modern advancements focus on enhancing its performance through innovative chemical admixtures and supplementary cementitious materials (SCMs). SCMs, often industrial byproducts like fly ash, silica fume, ground granulated blast furnace slag, and steel slag, replace a portion of Portland cement, reducing costs and environmental impact while improving concrete properties.
Silica fume, a particularly successful SCM, significantly enhances concrete's strength and durability, especially in high-strength applications. Steel slag, a byproduct of steel manufacturing, shows potential as an aggregate in concrete, despite its tendency to expand due to free lime and magnesium oxides. Proper treatment and the use of pozzolanic materials like silica fume can mitigate this expansion.
This study investigates the mechanical properties of concrete mixes using ACC brand slag cement, fly ash cement, and their blend (1:1), modified with 10% and 20% silica fume. Natural sand (zone II, IS 383-1982) serves as the fine aggregate, and steel slag (20 mm down) as the coarse aggregate, mixed in a 1:1.5:3 ratio. Tests on 7-day, 28-day, and 56-day compressive strengths, flexural strength, porosity, and capillary absorption were conducted.
Key findings include an increased water requirement with higher silica fume content, higher early strength gain with fly ash cement, and better later strength with slag cement. Silica fume reduces capillary absorption and porosity, particularly with fly ash cement.

Keywords: Concrete, Steel Slag, Silica Fume, Supplementary Cementitious Materials, Durability, Strength.

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1. Introduction

Concrete is a mixture of cement, sand, coarse aggregate, and water. Its success lies in its versatility, as it can be designed to withstand the harshest environments while taking on the most inspirational forms. Engineers and scientists are continually pushing its limits through the use of innovative chemical admixtures and various supplementary cementitious materials (SCMs).

Early SCMs consisted of natural, readily available materials like volcanic ash or diatomaceous earth. Engineering marvels such as the Roman aqueducts and the Coliseum are examples of this technique used by the Greeks and Romans. Today, most concrete mixtures incorporate SCMs, which are primarily byproducts or waste materials from other industrial processes.

2. Literature Review

Many works have been done to explore the benefits of using pozzolanic materials in making and enhancing the properties of concrete. M.D.A. Thomas, M.H.Shehata[1] et al. have studied the ternary cementitious blends of Portland cement, silica fume, and fly ash offer significant advantages over binary blends and even greater enhancements over plain Portland cement. Sandor Popovics[2] have studied the Portland cement-fly ash – silica fume systems in concrete andconcluded several beneficial effects of addition of silica fume to the fly ash cement mortar in terms of strength, workability and ultra sonic velocity test results.

Jan Bijen[3] have studied the benefits of slag and fly ash added to concrete made with OPC in terms of alkali-silica reaction, sulphate attack. L. Lam, Y.L. Wong, and C.S. Poon[4] in their studied entitled Effect of fly ash and silica fume on compressive and fracture behaviors of concrete had concluded enhancement in strength properties of concrete by adding different percentage of fly ash and silica fume.

Tahir Gonen and Salih Yazicioglu[5] studied the influence of binary and ternary blend of mineral admixtures on the short and long term performances of concrete and concluded many improved concrete properties in fresh and hardened states.

Mateusz Radlinski, Jan Olek and Tommy Nantung[6] in their experimental work entitled Effect of mixture composition and Initial curing conditions on the scaling resistance of ternary concrete have find out effect of different proportions of ingredients of ternary blend of binder mix on scaling resistance of concrete in low temperatures.

S.A. Barbhuiya, J.K. Gbagbo, M.I. Russeli, P.A.M. Basheer[7] studied the propertiesof fly ash concrete modified with hydrated lime and silica fume concluded that addition of lime and silica fume improve the early days compressive strength and long term strength developmentand durability of concrete.

3 Materials and Methodology

3.1.1 Silica Fume

Silica fume is a byproduct of the reduction of high-purity quartz with coke in electric arc furnaces during the production of silicon and ferrosilicon alloys. It consists of extremely fine particles, with a surface area of approximately 215,280 ft^2/lb (20,000 m^2/kg) when measured by nitrogen adsorption techniques, and particles approximately one hundredth the size of average cement particles. Due to its extreme fineness and high silica content, silica fume is a highly effective pozzolanic material.

3.1.1.1 Physical Properties of Silica Fume

The properties of silica fume were determined in laboratory. Specific gravity analysis is given below.

Table No. 3.1

Materials	Specific Gravity
Silica fume	2.27

3.1.1.2 Chemical Analysis of Silica Fume

The chemical analysis of silica fume is given below in Table No 3.2. It is also compared with ASTM.

Table No. 3.2

Silica fume	**ASTM-C-1240**	**Actual Analysis**
SiO_2	85% min	86.6%
LOI	6% max	2.5%
Moisture	3%	0.7%
Pozzplana Activity Index	105% min	129%
Specific Surface Area	>15 m^2/gm	22 m^2/gm
Bulk Density	550 to 700	600
+45	10% max	0.7%

3.1.2 Steel Slag

Steel slag is a byproduct of the steel production process, composed of silicates and oxides of unwanted elements in the steel's chemical composition. Approximately fifty million tons of Linz-Donawitz (LD) slag are produced annually worldwide as a residue from the Basic Oxygen Process (BOP).

Investigations have been conducted on the usability of steel slag as a construction material under both laboratory and practical conditions. The desired properties for such applications include high compressive strength, wear resistance, and resistance to climatic conditions. Volume stability is a critical criterion, significantly influenced by the free CaO and MgO contents in the slag. These oxides can react with water, causing hydration and subsequent volume expansion, which affects volume stability. This characteristic is a primary reason why steel slag aggregates are not suitable for use in Portland cement concrete. However, steel slag is widely used as an unbound aggregate for asphalt concrete pavement in many countries.

3.1.2.1 Sieve Analysis of Steel Slag

Sieve Analysis of steel slag in done to know the grade of the aggregate. This is given in Table 3.3 ***Table No. 3.3***

Sieve Size	**Wt Retain**	**Cum Wt Ret^n**	**% Cu wt Ret^n**	**% Passing**
2o mm	270 gm	0.270 kg	5.4	94.6
12.5 mm	3522 gm	3.792 kg	75.84	21.16
10 mm	790 gm	4.582 kg	91.64	8.36
4.75 mm	334 gm	4.916 kg	98.62	1.68
Total	5000 gm			

No gradation was found from the above test

3.1.2.2 Physical Properties of Steel Slag

The different physical properties of steel slag are given below in Table No 3.4.

Table No.3.4

Material	Specific Gravity	Water Absorption In %
Steel slag	3.35	1.1%

3.1.2.3 XRD Analysis of Steel Slag

From XRD Analysis of steel slag we can find what type Alkalis present. These are tabulated inTable No 3.5.

Table No.3.5

Chemical Compound	Visible	Ref-Code	Score
Na_2O	Yes	03-1074	10
K_2O	Yes	77-2176	10

From above table we can conclude that some amount of Alkalis present in steel slag.

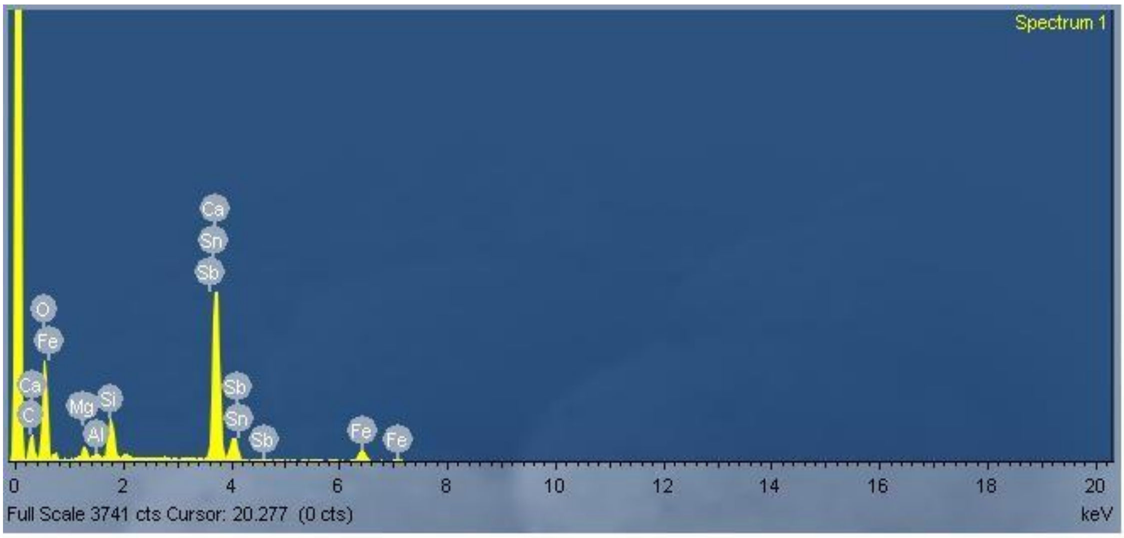

Figure 3.1 XRD Analysis of Steel Slag

4. Results and Discussions

4.1 Experimental Study on Mortar

Here we prepared mortar with ratio 1:3 from different types of cement + silica fume replacement as binder mix and sand as fine aggregate. Then its physical properties like capillary absorption consistency, compressive strength and porosity was predicted. These test results both in tabular form and graphical presentation are given below.

4.1.1 Normal Consistency for Mortar

Normal consistency of different binder mixes was determined using the following procedure referring to IS 4031: part 4 (1988):

1. 300 gm of sample coarser than 150 micron sieve is taken.
2. Approximate percentage of water was added to the sample and was mixed thoroughly for 2-3 minutes.
3. Paste was placed in the vicat‟s mould and was kept under the needle of vicat‟s apparatus.
4. Needle was released quickly after making it touch the surface of the sample.
5. Check was made whether the reading was coming in between 5-7 mm or not and same process was repeated if not
6. The percentage of water with which the above condition is satisfied is called normalconsistency.

Normal consistency of different binder mixes were tabulated below in Table No. 4.1.

Table No.4.1

Mix	**Description**	**Cement (Grams)**	**Silica Fume (Grams)**	**Consistency (%)**
SC0	SC	300	00	31.5
SC10	SC with 10% SF	270	30	35
SC20	SC with 20% SF	240	60	40.5
FC0	FC	300	00	37.5
FC10	FC with 10% SF	270	30	47
FC20	FC with 20% SF	240	60	55.5
SFC0	SC:FC (1:1)	150 each	00	36.5
SFC10	SC:FC (1:1) with 10% SF	135 each	30	41.5
SFC20	SC:FC (1:1) with 20% SF	120 each	60	47.5

Where, SC = slag cement
FC = fly ash cement
SF = silica fume

SFC = slag and fly ash cement
SC0 = Slag cement with 0% silica fume replacement.
SC10 = Slag cement with 10% silica fume replacement.

5. Conclusion and Scope of Work

5.1 Conclusion

- **Strength Improvement:** Inclusion of silica fume enhances the strength of various binder mixes by increasing their density.
- **Early and Later Strength Gain:** Silica fume addition boosts the early strength gain of fly ash cement and increases the later age strength of slag cement.
- **Combined Strength Development:** An equal blend of slag and fly ash cements results in improved overall strength development at any stage.
- **Reduced Capillary Absorption and Porosity:** Silica fume addition to any binder mix reduces capillary absorption and porosity due to the formation of denser and crystalline hydrates from the reaction between silica fume and lime in the cement.
- **Effect of Silica Fume Dosage:** Increasing the silica fume replacement up to 20% further decreases capillary absorption and porosity in mortar.
- **Strength Reduction in Steel Slag Concrete:** Silica fume addition to concrete with steel slag as coarse aggregate reduces the concrete's strength at any age.
- **Mixing and Compaction Issues:** The sticky nature of the mix due to silica fume can cause void formation during mixing and compacting, as entrapped air cannot escape easily. Using a needle vibrator may help minimize this problem.
- **Alkali-Aggregate Reaction:** The reduction in strength is primarily due to the alkali-aggregate reaction between the binder matrix and the steel slag used as coarse aggregate. Silica fume reacts with alkalis and lime, forming a gel that weakens the bond between aggregate and binder matrix, especially at higher doses of silica fume.
- **Cohesiveness and Voids:** Fly ash cement combined with silica fume makes the concrete more cohesive or sticky, leading to more voids compared to slag cement and silica fume mixes. This results in higher capillary absorption and porosity in fly ash and silica fume mixes.
- **Steel Slag Replacement:** Total replacement of natural coarse aggregate with steel slag is not recommended. Partial replacement with properly treated steel slag and fly ash cement may produce high-strength concrete.
- **Steel Slag Treatment:** Proper treatment of steel slag, including stockpiling in the open for at least one year, allows free CaO and MgO to hydrate, reducing later-age expansion.
- **Chemical Analysis:** A thorough chemical analysis of steel slag is recommended to identify alkalis that may negatively impact the bond between the binder matrix and the aggregate.

5.2 Scope of the Work

- **Optimization of Silica Fume Content:** Investigate the optimal percentage of silica fume replacement in various binder mixes to maximize strength and durability while minimizing negative effects on workability and cohesion.
- **Binder Mix Design:** Develop and test various binder mix designs using different proportions of slag cement, fly ash cement, and their blends, incorporating silica fume to assess their mechanical properties.
- **Aggregate Analysis:** Conduct comprehensive studies on the chemical composition of steel slag to understand its interaction with different binder mixes, focusing on alkali content and its effect on concrete properties.
- **Treatment Methods for Steel Slag:** Explore and optimize treatment methods for steel slag to enhance its suitability as a coarse aggregate in concrete, including methods to reduce free CaO and MgO content.
- **Mechanical Properties Testing:** Perform extensive testing on the mechanical properties of concrete containing treated steel slag, fly ash cement, and silica fume at different ages, focusing on compressive strength, flexural strength, capillary absorption, and porosity.
- **Durability Assessment:** Evaluate the long-term durability of concrete mixes containing treated steel slag and silica fume, considering factors such as resistance to climatic conditions, wear strength, and volume stability.

- **Field Applications:** Conduct field trials to validate laboratory findings and assess the practical performance of concrete mixes containing silica fume and treated steel slag in real-world construction scenarios.
- **Environmental Impact:** Assess the environmental benefits of using industrial byproducts like silica fume and steel slag in concrete, including the reduction in CO_2 emissions and the sustainable utilization of waste materials.
- **Comparative Analysis:** Compare the performance of concrete mixes containing different SCMs, such as fly ash, slag cement, and silica fume, to determine the most effective combinations for specific applications.
- **Guidelines Development:** Develop guidelines and recommendations for the construction industry on the effective use of silica fume and treated steel slag in concrete to achieve desired performance characteristics while ensuring sustainability.

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