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Experimental Study on the Effect of Silica Fume on Strength and Durability of M40 Grade Ready Mix Concrete

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Abstract: The present research investigates the influence of silica fume as a partial replacement of cement on the mechanical and durability properties of M40 grade Ready Mix Concrete (RMC). Five concrete mixes were designed with 0%, 5%, 10%, 15%, and 20% silica fume by weight of cement. The experimental program involved testing for compressive strength, split tensile strength, flexural strength, water absorption, acid resistance, and chloride permeability at various curing ages (7, 28, and 56 days). Results indicate that the mechanical strength and durability characteristics improved significantly up to a 10% replacement level, beyond which a decline was observed. The 10% silica fume mix exhibited the highest 28-day compressive strength of 50.9 MPa, about 11.6% higher than the control mix, along with reduced water absorption (2.35%) and chloride permeability (1850 Coulombs). The findings confirm that silica fume enhances the microstructure and durability of concrete and is suitable for high-performance and sustainable construction applications.
Keywords: Silica fume, Ready mix concrete, Compressive strength, Durability, Sustainable concrete, Supplementary cementitious material.

I. INTRODUCTION

Concrete is the most widely used construction material due to its versatility, strength, and affordability. However, its conventional form exhibits limitations such as low tensile strength, high permeability, and susceptibility to environmental degradation. In the pursuit of sustainable and durable construction materials, supplementary cementitious materials (SCMs) such as fly ash, ground granulated blast furnace slag (GGBS), and silica fume have been extensively studied. Silica fume, a by-product of the silicon and ferrosilicon industry, is an ultrafine amorphous form of silicon dioxide with high pozzolanic reactivity. When added to concrete, it reacts with calcium hydroxide liberated during cement hydration to form additional calcium silicate hydrate (C–S–H) gel, enhancing strength and reducing permeability. Its micro-filler effect also refines the pore structure, leading to improved durability against chloride ingress, acid attack, and water absorption. This study aims to evaluate the mechanical and durability performance of M40 grade Ready Mix Concrete (RMC) incorporating silica fume at varying replacement levels. The results provide insight into the optimum proportion that balances strength, workability, and long-term durability, thereby promoting sustainable construction practices.

II. MATERIALS AND METHODOLOGY

The main objective of this study is to investigate the influence of silica fume as a partial replacement of cement on the mechanical and durability properties of M40 grade Ready Mix Concrete (RMC). The methodology has been developed to systematically study the effect of silica fume replacement at 0%, 5%, 10%, 15%, and 20% by weight of cement. The proposed methodology encompasses selection and characterization of materials, mix design, concrete preparation, specimen casting, curing, testing, and analysis. Each step is carefully planned to ensure the accuracy, reproducibility, and relevance of the experimental results, while maintaining compliance with Indian Standard codes such as IS 10262:2019, IS 516:1959, and IS 456:2000. The methodology has been designed to not only evaluate mechanical performance in terms of compressive, split tensile, and flexural strength, but also to examine durability characteristics including water absorption, acid resistance, and permeability, providing a holistic understanding of silica fume-modified RMC.

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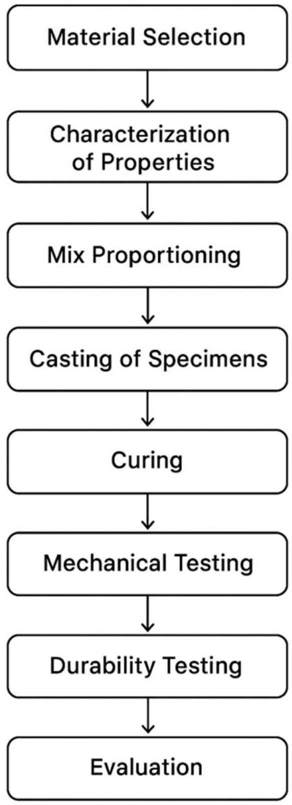

Flowchart 3.1: Proposed Methodology

A. Materials Used

The selection of appropriate materials is a critical step in ensuring the successful production of high-performance M40 grade Ready Mix Concrete (RMC), especially when investigating the effect of silica fume as a partial replacement of cement. For this study, all materials have been carefully chosen based on their availability in the local Indian context, compliance with relevant Indian Standards, and their ability to produce concrete with consistent workability, strength, and durability. The characteristics of each material directly influence the fresh and hardened properties of concrete, and their proper selection and testing are fundamental to achieving the objectives of this research. The materials used in this study include cement, fine aggregate, coarse aggregate, silica fume, water, and superplasticizer, each of which is described in detail below.

1) Cement: The primary binder used in this study is Ordinary Portland Cement (OPC) 53 grade, which conforms to the specifications of IS 12269:2013. OPC 53 grade cement is widely used in India for producing high-strength concrete due to its higher compressive strength and faster setting characteristics compared to lower grades. Prior to its use in mix preparation, the cement was subjected to preliminary tests to determine its fineness, initial and final setting times, consistency, and compressive strength, ensuring that it meets the required standards. The chemical composition of the cement was also examined to verify the presence of adequate clinker minerals and to ensure that the cement would react efficiently with silica fume during pozzolanic reactions. The cement provides the primary binding action in concrete, and its quality is essential to achieving the targeted M40 grade strength, as any variation in cement properties could affect hydration, microstructure development, and long-term durability.
2) Fine Aggregate: Natural river sand conforming to Zone II of IS 383:2016 was used as the fine aggregate. The sand is well-graded, clean, and free from organic impurities, silt, or clay, which ensures uniform mixing and good bonding with the cement paste. The particle size distribution of the fine aggregate was analyzed to confirm its grading, which plays a crucial role in achieving dense packing, reducing voids, and improving workability. Fine aggregates contribute to the overall cohesiveness and finishability of the concrete, and any variation in sand quality can significantly influence the slump, bleeding, and setting characteristics of the mix. In this study, the selected river sand provided a smooth texture to the fresh concrete while maintaining proper strength development and durability in the hardened state.

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3) Coarse Aggregate: Crushed angular aggregates of 20 mm and 10 mm nominal sizes were used as the coarse aggregate, in accordance with IS 383:2016. The aggregates were carefully washed and screened to remove dirt, dust, and other impurities that could interfere with the hydration process or weaken the bond between aggregate and cement paste. Coarse aggregates form the skeleton of the concrete, providing bulk, dimensional stability, and resistance to mechanical loads. Angular aggregates were preferred over rounded ones to ensure better mechanical interlock and higher compressive strength. The aggregates were also tested for specific gravity, water absorption, and bulk density to ensure consistency in the concrete mix design. Proper selection of coarse aggregate is essential for achieving targeted strength, reducing segregation, and improving the durability of concrete under various environmental exposures.
4) Silica Fume: Silica fume is an ultrafine industrial by-product obtained during the production of silicon and ferrosilicon alloys. It is composed primarily of amorphous silicon dioxide (SiO_2), which exhibits high pozzolanic activity. In this study, silica fume was used as a partial replacement of cement at various percentages (0%, 5%, 10%, 15%, and 20%). The extremely fine particles of silica fume act as micro-fillers, filling the voids between cement grains and improving the density of the cement matrix. Additionally, silica fume reacts with calcium hydroxide ($Ca(OH)_2$) produced during cement hydration to form additional calcium silicate hydrate (C–S–H) gel, which significantly enhances strength and reduces porosity. Prior to mixing, the silica fume was tested for specific surface area, pozzolanic activity, and chemical composition to ensure quality and consistency. Its proper dispersion in the mix is crucial, as agglomeration can lead to uneven performance and reduced mechanical properties. The inclusion of silica fume is central to this study as it directly affects the mechanical, durability, and workability characteristics of M40 grade RMC.
5) Water: Water plays a vital role in concrete as it participates in the hydration of cement and influences both the workability and durability of the mix. For this study, potable water free from impurities, salts, and organic matter, conforming to IS 456:2000, was used for both mixing and curing purposes. The quality and quantity of water were carefully controlled to maintain the desired water-cement ratio for M40 grade concrete, which directly impacts the strength, porosity, and durability of the hardened concrete. Adequate water ensures proper hydration, facilitates uniform mixing, and enhances the dispersion of silica fume particles throughout the concrete matrix. Any contamination in water can adversely affect the microstructure, setting time, and chemical stability of the concrete, which is why high-quality water is essential for this experimental study.

B. Tests Conducted

The following tests were conducted on all samples:
1) Compressive Strength Test (IS 516:1959)
2) Split Tensile Strength Test (IS 5816:1999)
3) Flexural Strength Test (IS 516:1959)
4) Water Absorption Test
5) Acid Resistance Test (5% H_2SO_4 solution, 28 days exposure)
6) Rapid Chloride Permeability Test (ASTM C1202)

All specimens were cured in water and tested at 7, 28, and 56 days.

C. Mix Proportions

The concrete mix was designed as per IS 10262:2019 for M40 grade with a target mean strength of 48.25 MPa and a water–cement ratio of 0.40. Five mixes were prepared by replacing cement with silica fume at 0%, 5%, 10%, 15%, and 20%.

D. Sample Details

Sample ID	Silica Fume Replacement (%)	Description
S1	0	Control Mix
S2	5	Low Replacement
S3	10	Optimum Replacement
S4	15	Moderate-High Replacement
S5	20	High Replacement

III. RESULTS AND DISCUSSION

A. *Compressive Strength*

Curing Age (Days)	S1 (0%)	S2 (5%)	S3 (10%)	S4 (15%)	S5 (20%)
7	32.4	34.2	35.8	33.6	30.2
28	45.6	48.7	50.9	47.5	42.3
56	47.1	51.0	53.7	49.0	44.0

The compressive strength increased with silica fume content up to 10%, followed by a decline. The 10% mix achieved a 28-day strength of 50.9 MPa, approximately 11.6% higher than the control. The improvement is attributed to the formation of secondary C–S–H gel and densification of the matrix.

B. *Split Tensile Strength*

Curing Age (Days)	S1	S2	S3	S4	S5
7	2.85	2.95	3.00	2.85	2.65
28	3.75	3.95	4.10	3.85	3.60
56	3.90	4.10	4.25	3.95	3.80

The maximum split tensile strength (4.10 MPa at 28 days) was observed at 10% silica fume. The increase of about 9.3% over the control mix is due to improved interfacial bonding between the cement paste and aggregates.

C. *Flexural Strength*

Curing Age (Days)	S1	S2	S3	S4	S5
7	4.80	4.95	5.10	4.85	4.50
28	5.80	6.05	6.35	6.00	5.60
56	6.00	6.25	6.55	6.10	5.80

The flexural strength trend followed compressive strength behavior, with the highest value at 10% replacement. The improvement results from the densification of the interfacial transition zone (ITZ).

D. *Durability Studies*

1) *Water Absorption*

Sample ID	Water Absorption (%)
S1	3.10
S2	2.65
S3	2.35
S4	2.45
S5	2.60

Water absorption decreased with silica fume addition up to 10%, indicating improved impermeability due to refined pore structure.

2) *Acid Resistance (5% H_2SO_4 Solution)*

Sample ID	% Weight Loss
S1	2.85
S2	2.25
S3	1.90
S4	2.05
S5	2.20

Silica fume improved acid resistance by reducing calcium hydroxide in the concrete matrix. The 10% mix exhibited the least weight loss.

3) Rapid Chloride Permeability Test (RCPT)

Sample ID	Charge Passed (Coulombs)	Permeability Rating
S1	3100	Moderate
S2	2300	Low
S3	1850	Low
S4	2050	Low
S5	2200	Low

The RCPT results showed that silica fume significantly reduced chloride ion permeability, confirming enhanced durability.

Overall Discussion

The incorporation of silica fume up to 10% significantly enhanced both the mechanical and durability performance of M40 grade RMC. Beyond 10%, the reduction in workability and incomplete hydration caused a decline in strength and durability. Thus, 10% silica fume replacement is identified as the optimum dosage for achieving superior performance.

IV. CONCLUSION

1) The inclusion of silica fume reduced workability but enhanced strength and durability when combined with superplasticizers.
2) The 10% silica fume replacement achieved maximum compressive strength (50.9 MPa at 28 days), about 11.6% higher than the control mix.
3) Split tensile and flexural strengths also improved by approximately 9–10% at the same replacement level.
4) Durability characteristics such as water absorption, chloride permeability, and acid resistance improved significantly at 10% replacement.
5) The microstructural densification due to the pozzolanic and filler effects of silica fume contributed to improved impermeability and reduced porosity.
6) The 10% silica fume mix is recommended for high-performance and sustainable RMC applications.

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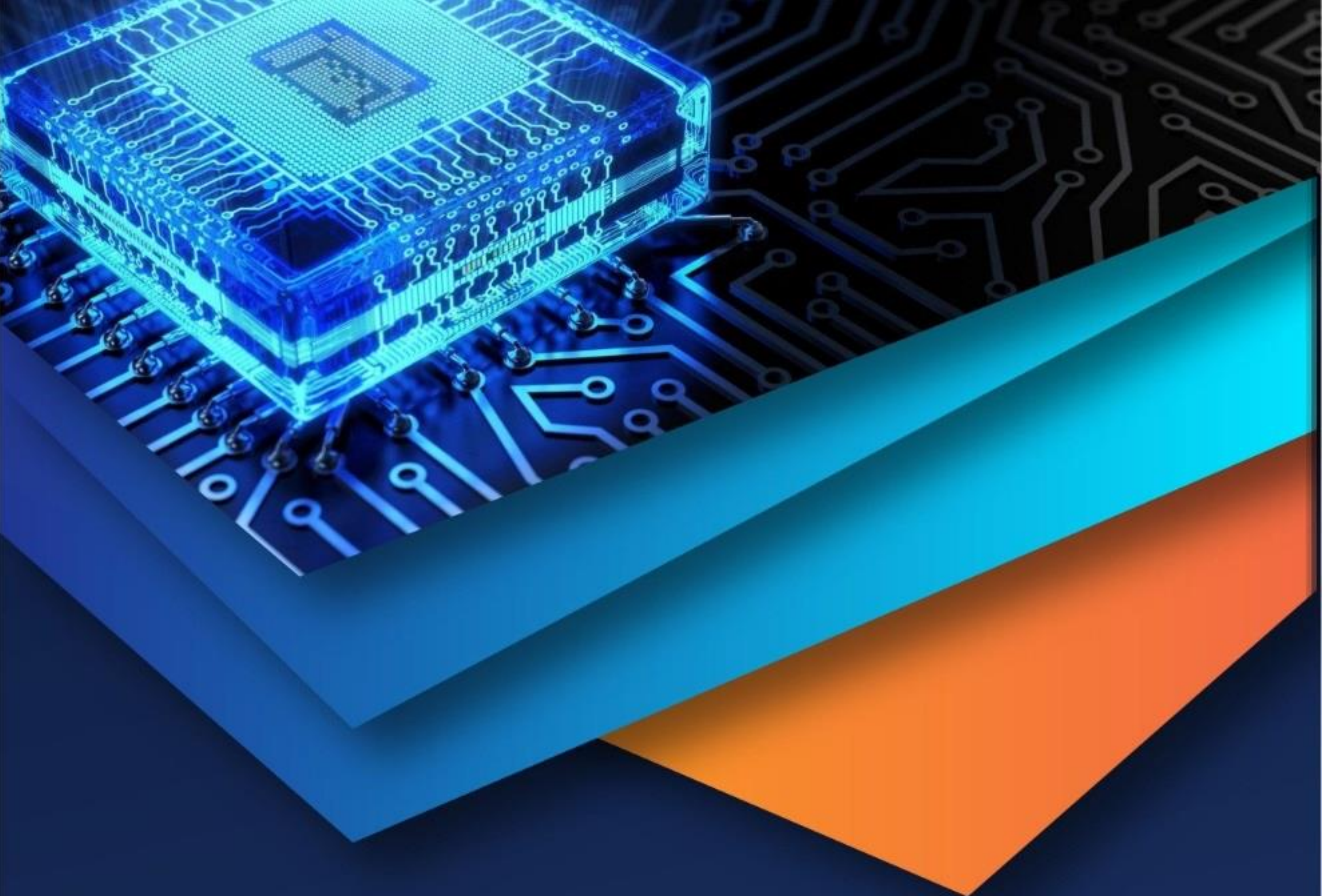

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