IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

Enhancing Concrete Performance Through Silica Fume And Steel Fiber: Strength And Durability Evaluation

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ABSTRACT

This research project focuses on evaluating the impact of incorporating silica fume and steel fiber into concrete to enhance its performance. Silica fume, a fine material, is added to improve the workability and strength of the concrete, while steel fiber is used as a partial replacement for cement. The study involves testing different concrete mixtures, including control and variation mixes, to assess the effects of silica fume and steel fiber on the compressive strength, flexural strength, and splitting tensile strength of the concrete. The research findings indicate that the inclusion of silica fume and steel fiber resulted in concrete with increased strength and durability compared to traditional concrete, suggesting potential benefits for both performance enhancement and environmental sustainability.

Keywords: Concrete, Silica Fume, Steel Fiber

Introduction

Concrete, a highly versatile construction material composed of cement, sand, coarse aggregate, and water, is celebrated for its durability and its ability to adapt to various structural designs. The production of cement involves heating raw materials in a kiln to form clinker, which contains compounds known as "bogue compounds." The versatility of concrete is continuously improved by integrating innovative chemical admixtures and supplementary cementitious materials (SCMs) to meet the demands of challenging environments and complex architectural designs. In India, the cement industry has shown consistent growth, with a 7% increase in 2018 and a 6.2% rise in 2019. The demand for cement surged by 6% in 2020, driven by large infrastructure projects and government-sponsored affordable housing schemes. India has become the second-largest cement producer globally, with a production capacity of 455 million tons in 2017-18. However, the increased demand for cement leads to higher fuel consumption, energy inputs, lime excavation, and CO2 emissions, contributing to environmental issues such as air pollution and depletion of natural resources. To address these challenges, there is a growing emphasis on sustainable practices in cement production, including the use of supplementary materials like silica fume and steel fiber. These materials not only enhance concrete performance but also help reduce CO2 emissions, energy consumption, fuel usage, and air pollution. Additionally, utilizing industrial by-products in concrete production can mitigate disposal problems and preserve fertile land from degradation. These efforts aim to promote sustainable practices in the construction industry while meeting the increasing demand for cement. The rise in environmental pollution has led to an increase in industrial waste and secondary by-products. Materials such as micro silica, fly ash, silica fume, and ground granulated blast furnace slag can serve as Supplementary Cementitious Materials (SCMs). Their incorporation into concrete construction not only helps reduce pollution but also enhances the properties of concrete in both its fresh and hardened states. SCMs can be classified into two types based on their reaction mechanism: hydraulic and pozzolanic. Hydraulic materials, like silica fume, react directly with water to form cementitious compounds. Pozzolanic materials, while lacking inherent cementitious properties, react with calcium hydroxide when combined with cement or lime to form products with cementitious characteristics. Silica fume is particularly valued for its ability to produce high-strength concrete and is used as a cement replacement to reduce cement content and as an additive to improve concrete properties. By leveraging the potential of these SCMs, concrete constructions can achieve structural integrity while also contributing to environmental sustainability by repurposing industrial by-products and reducing dependence on traditional cement production.

Literature Review

Numerous studies have examined the performance of concrete with silica fume as a partial replacement. However, research combining silica fume and steel fiber is limited and relatively new, with only a few investigations to date. In a study by Ashokan, Rajendran, and Dhairiyasamy (2023), steel fiber-reinforced concrete was enhanced by integrating nano-silica. Incorporating steel microfibers at 1-2% volume fractions improved compressive, tensile, and flexural strength, as well as fracture energy. Optimal results were achieved with 2% steel fibers and 1% nano-silica, significantly enhancing compressive strength (122.5 MPa), tensile strength (25.4 MPa), and modulus of elasticity (42.7 GPa), while also increasing ductility and energy absorption. Thiyaneswaran et al. (2022) studied steel fiber in high-performance concrete and found that it enhanced mechanical strength and durability but reduced workability. They introduced fly ash (20-30%) to improve workability and sustainability. Comparative tests showed modified mixes outperformed traditional concrete in mechanical properties and reduced greenhouse gas emissions. Prathap, Kumar, and Dr. S.M.V (2022) investigated silica fume in M35 grade concrete and found 10% silica fume to be optimal for compressive strength. Adding crimped steel fibers (0.2%-2%) to this mix further improved mechanical properties. The study highlighted the combined benefits of mineral admixtures and steel fibers in enhancing concrete performance. Ali (2021) evaluated different fibers (steel, glass, carbon, polypropylene) with and without silica fume. Silica fume (10% replacement) improved fibers' efficacy in resisting loads. Steel fiber-reinforced concrete showed superior mechanical performance at 28 days, while carbon fiber-reinforced concrete excelled at 180 days. Silica fume also improved durability by reducing water absorption and chloride penetration. Joshi et al. (2015) found that adding steel fibers reduced workability but increased compressive and tensile strength across different concrete grades. Superplasticizers were used to counteract reduced workability, demonstrating that steel fibers can significantly enhance concrete strength when properly managed. Chaitanyakumar et al. (2016) discovered that glass fibers reduced cracking and increased workability and strength properties in M-20 grade concrete, especially at 1% fiber addition. The use of waste glass as fiber also promoted sustainable practices. Lei, Zhou, and Sun (2015) found that higher steel fiber content increased flexural strength, while aggregate gradation primarily affected compressive strength. Lower water-cement ratios improved compressive strength, highlighting the complex interactions affecting concrete's mechanical properties. Konapure and Dasari (2015) showed that increasing silica fume content up to 15% improved compressive and flexural strength but required higher dosages of chemical admixtures for workability. The study emphasized the importance of balancing silica fume content and admixture dosage for optimal concrete performance. Vasudev and Vishnuram (2013) found that fiber percentage inconsistently affected compressive strength but increased tensile strength by 20-22% with 0.5% fiber content in M20 and M40 mixes. They advocated using recycled scraps for fiber production and partially replacing cement with fly ash to enhance sustainability in concrete production.

Overall, these studies demonstrate the significant benefits of combining silica fume and steel fibers in concrete, enhancing both mechanical properties and sustainability. This research aims to further explore this promising combination.

Material and Methods

Concrete, a composite material made by mixing cement, fine aggregate, coarse aggregate, and water, is versatile for various structures due to its adjustable constituent proportions. Aggregates, both coarse and fine, form the bulk of concrete mixtures, with coarse aggregates larger than 4.75mm (used sizes: 10mm and 20mm) and fine aggregates being sand-sized particles less than 4.75mm. Cement, primarily Ordinary Portland Cement (OPC), undergoes chemical reactions to form compounds like C-S-H and Ca(OH)2, crucial for concrete's strength. Mineral admixtures like silica fume enhance concrete by reducing permeability and increasing strength, while steel fibers improve its tensile properties. Chemical admixtures, particularly superplasticizers, are used to reduce water content and enhance workability. Sieve analysis for both fine and coarse aggregates ensures proper particle size distribution, and proportion mixes are designed for specific strengths, with variations including silica fume and steel fibers. Workability tests, including the slump test, assess fresh concrete's ease of handling. Hardened concrete tests such as density, compressive strength (using cube specimens), flexural strength (using beam specimens), and splitting tensile strength (using cylinder specimens) are conducted to evaluate its performance, following relevant IS codes.

Results and discussion

The results of the experimental work are analyzed, focusing on various blends and mixes. Different mixes were prepared with two variations in cement: one where silica fume and steel fiber replaced percentages of cement ranging from 2.5% to 10% in 2.5% intervals for both M35 and M40 concrete mixes. Tests conducted include slump, density, compressive strength, flexural strength, and splitting tensile strength.

Results of Fresh Concrete

Workability Test Result

The consistency of fresh concrete during mixing, handling, delivery, and placement is crucial for its performance. Workability, a relative parameter defined by consistency, is essential for cost-effective handling, pouring, placing, finishing, and ensuring maximum plasticity and flowability with super plasticizers. It also minimizes segregation and ensures good surface smoothing properties. The slump test measures deformability of fresh concrete. The design aimed for a slump of 100mm-120mm, but the actual slump observed was 125mm for M35 grade concrete and 135mm for M40 grade concrete, with variations noted across different mixes.

For M35 grade concrete:

- 100% OPC: 125mm
- 95% OPC + 2.5% silica fume + 2.5% steel fiber: 127mm
- 90% OPC + 5% silica fume + 5% steel fiber: 142mm
- 85% OPC + 7.5% silica fume + 7.5% steel fiber: 146mm
- 80% OPC + 10% silica fume + 10% steel fiber: 150mm

For M40 grade concrete:

- 100% OPC: 135mm
- 95% OPC + 2.5% silica fume + 2.5% steel fiber: 137mm
- 90% OPC + 5% silica fume + 5% steel fiber: 150mm
- 85% OPC + 7.5% silica fume + 7.5% steel fiber: 155mm
- 80% OPC + 10% silica fume + 10% steel fiber: 160mm

Results of Hardened Concrete

Density Test Result

The density of hardened concrete was measured using cube, cylinder, and beam specimens, which were cleaned and weighed before testing. Average weights for M35 and M40 grade concretes were recorded as follows: cube (8.55 kg), cylinder (12.70 kg), and beam (39.30 kg) after 28 days.

For M35 grade concrete:

- 100% OPC: 2415.33 kg/m^3
- 95% OPC + 2.5% silica fume + 2.5% steel fiber: 2417.12 kg/m^3
- 90% OPC + 5% silica fume + 5% steel fiber: 2423.15 kg/m^3
- 85% OPC + 7.5% silica fume + 7.5% steel fiber: 2443.86 kg/m^3
- 80% OPC + 10% silica fume + 10% steel fiber: 2443.2 kg/m^3

For M40 grade concrete:

- 100% OPC: 2418 kg/m^3
- 95% OPC + 2.5% silica fume + 2.5% steel fiber: 2436.54 kg/m^3
- 90% OPC + 5% silica fume + 5% steel fiber: 2427.99 kg/m^3
- 85% OPC + 7.5% silica fume + 7.5% steel fiber: 2445.20 kg/m^3
- 80% OPC + 10% silica fume + 10% steel fiber: 2450.12 kg/m^3

Compressive Strength

The compressive strength was tested on cube specimens (150mm x 150mm x 150mm) after 7 and 28 days of curing.

For M35 grade concrete (7 days):

- 100% OPC: 29.55 N/mm^2
- 95% OPC + 2.5% silica fume + 2.5% steel fiber: 30.00 N/mm^2
- 90% OPC + 5% silica fume + 5% steel fiber: 31.33 N/mm^2
- 85% OPC + 7.5% silica fume + 7.5% steel fiber: 31.33 N/mm^2
- 80% OPC + 10% silica fume + 10% steel fiber: 30.66 N/mm^2

For M40 grade concrete (7 days):

- 100% OPC: 32.66 N/mm²
- 95% OPC + 2.5% silica fume + 2.5% steel fiber: 33.55 N/mm²
- 90% OPC + 5% silica fume + 5% steel fiber: 34.33 N/mm²
- 85% OPC + 7.5% silica fume + 7.5% steel fiber: 34.77 N/mm²
- 80% OPC + 10% silica fume + 10% steel fiber: 34.44 N/mm²

For M35 grade concrete (28 days):

- 100% OPC: 43.30 N/mm²
- 95% OPC + 2.5% silica fume + 2.5% steel fiber: 44.25 N/mm²
- 90% OPC + 5% silica fume + 5% steel fiber: 44.54 N/mm²
- 85% OPC + 7.5% silica fume + 7.5% steel fiber: 45.14 N/mm²
- 80% OPC + 10% silica fume + 10% steel fiber: 45.16 N/mm²

For M40 grade concrete (28 days):

- 100% OPC: 48.29 N/mm²
- 95% OPC + 2.5% silica fume + 2.5% steel fiber: 48.93 N/mm²
- 90% OPC + 5% silica fume + 5% steel fiber: 49.79 N/mm²
- 85% OPC + 7.5% silica fume + 7.5% steel fiber: 50.23 N/mm²
- 80% OPC + 10% silica fume + 10% steel fiber: 50.26 N/mm²

Flexural Strength

The flexural strength was tested on beam specimens (700mm x 150mm x 150mm) after 28 days.

For M35 grade concrete:

- 100% OPC: 5.96 N/mm²
- 95% OPC + 2.5% silica fume + 2.5% steel fiber: 6.58 N/mm²
- 90% OPC + 5% silica fume + 5% steel fiber: 6.76 N/mm²
- 85% OPC + 7.5% silica fume + 7.5% steel fiber: 7.12 N/mm²
- 80% OPC + 10% silica fume + 10% steel fiber: 7.16 N/mm²

For M40 grade concrete:

- 100% OPC: 6.85 N/mm²
- 95% OPC + 2.5% silica fume + 2.5% steel fiber: 7.47 N/mm²
- 90% OPC + 5% silica fume + 5% steel fiber: 7.83 N/mm²

- 85% OPC + 7.5% silica fume + 7.5% steel fiber: 8.03 N/mm^2
- 80% OPC + 10% silica fume + 10% steel fiber: 8.12 N/mm^2

Splitting Tensile Strength

The splitting tensile strength was tested on cylinder specimens (300mm length x 150mm diameter) after 28 days.

For M35 grade concrete:

- 100% OPC: 2.70 N/mm^2
- 95% OPC + 2.5% silica fume + 2.5% steel fiber: 2.89 N/mm^2
- 90% OPC + 5% silica fume + 5% steel fiber: 2.97 N/mm^2
- 85% OPC + 7.5% silica fume + 7.5% steel fiber: 3.02 N/mm^2
- 80% OPC + 10% silica fume + 10% steel fiber: 3.20 N/mm^2

For M40 grade concrete:

- 100% OPC: 2.97 N/mm^2
- 95% OPC + 2.5% silica fume + 2.5% steel fiber: 3.30 N/mm^2
- 90% OPC + 5% silica fume + 5% steel fiber: 3.54 N/mm^2
- 85% OPC + 7.5% silica fume + 7.5% steel fiber: 3.68 N/mm^2
- 80% OPC + 10% silica fume + 10% steel fiber: 3.78 N/mm^2

Conclusion

The slump of the concrete mix increased with the partial replacement of silica fume and steel fiber in OPC. This increase is due to the reduction in water demand caused by the cement replacement with silica fume and steel fiber. At all percentage intervals, the slump was higher compared to the control mix. For M35 grade, a slump of 127mm was achieved with a 5% partial replacement of silica fume and steel fiber, while a slump of 150mm required a 20% partial replacement. Similarly, for M40 grade, a slump of 137mm was achieved with a 5% partial replacement of silica fume and steel fiber, while a slump of 160mm required a 20% partial replacement.

The density of both M35 and M40 grade concrete specimens increased with the partial replacement of silica fume and steel fiber in OPC compared to the control mix. This increase is attributed to the development of gel pores, resulting in a denser internal system. The compressive strength, flexural strength, and splitting tensile strength were greater in the specimens with partial replacement compared to the normal concrete specimens of OPC.

The compressive strength was higher in specimens with silica fume and steel fiber replacement in OPC compared to the control mix for both M35 and M40 grades. The maximum compressive strengths were 45.37 N/mm^2 for M35 grade and 50.42 N/mm^2 for M40 grade, both achieved with replacements, representing a 5% increase compared to their respective control mixes.

The flexural strength was higher in specimens with silica fume and steel fiber replacement in OPC compared to the control mix for both M35 and M40 grades. The maximum flexural strengths were 7.29

N/mm² for M35 grade and 8.72 N/mm² for M40 grade, with increases of 22% and 27% respectively compared to their respective control mixes.

The split tensile strength was higher in specimens with silica fume and steel fiber replacement in OPC compared to the control mix for both M35 and M40 grades. The maximum split tensile strengths were 3.20 N/mm² for M35 grade and 3.78 N/mm² for M40 grade, with increases of 18.5% and 27.27% respectively compared to their respective control mixes.

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