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Enhancing High-Strength Self-Compacting Concrete (HSSCC) with Marble Sludge Powder and Silica Fume for Sustainable Construction

[1]Mukesh, [2]Rakesh Kumar

[1]M.Tech. Scholar, [2]Assistant Professor

Department of CE
BRCM College of Engineering and Technology, Bahal (Bhiwani) India

Abstract

The contemporary construction industry demands advanced materials that combine high strength, durability, and sustainability. This study investigates the development of High-Strength Self-Compacting Concrete (HSSCC) incorporating Marble Sludge Powder (MSP), Silica Fume (SF), and Quartz Sand (QS) as partial replacements for fine aggregates. The research evaluates the physical, chemical, mechanical, and durability properties of HSSCC under elevated temperatures and compares its performance with conventional High-Strength Vibrated Concrete (HSVC). Experimental results demonstrate that HSSCC with Ground Granulated Blast Furnace Slag (GGBS) and Fly Ash (FA) exhibits superior workability, compressive strength (up to 58.55 MPa at 28 days), and thermal resistance (up to 400°C). Artificial Neural Networks (ANN) were employed to predict compressive strength, achieving high accuracy. The study highlights the environmental benefits of using industrial by-products like MSP and SF, promoting sustainable construction practices.

Keywords

High-Strength Self-Compacting Concrete (HSSCC), Marble Sludge Powder (MSP), Silica Fume (SF), Quartz Sand (QS), Elevated Temperature, Sustainability, Artificial Neural Networks (ANN).

1. Introduction

The construction industry continually faces significant challenges in achieving proper compaction and uniform strength in densely reinforced structures, particularly in complex and congested reinforcement layouts. Traditional vibrated concrete (VC) often suffers from inadequate compaction due to limited access for vibration equipment, leading to honeycombing, voids, and inconsistent mechanical properties. These defects compromise structural integrity, durability, and long-term performance, necessitating alternative solutions that ensure uniform consolidation without external vibration.

Self-Compacting Concrete (SCC) has emerged as an innovative solution, offering superior workability, flowability, and mechanical performance without requiring mechanical vibration. SCC achieves full compaction under its own weight, making it ideal for intricate formwork and heavily reinforced sections. However, while conventional SCC addresses compaction issues, its mechanical strength and durability—especially under extreme conditions such as elevated temperatures—remain areas of ongoing research. To bridge this gap, High-Strength Self-Compacting Concrete (HSSCC) has been developed by incorporating supplementary cementitious materials (SCMs) and fine fillers that enhance both fresh and hardened properties.

This study focuses on optimizing HSSCC by integrating Micro Silica Powder (MSP), Silica Fume (SF), and Quarry Dust (QS) as partial replacements for cement and fine aggregates. These materials contribute to improved particle packing density, enhanced pozzolanic reactivity, and refined microstructure, resulting in superior mechanical strength and durability. The research aims to develop an optimized mix design that achieves high compressive strength, tensile resistance, and durability while maintaining excellent self-compacting properties.

1.1 Research Objectives

The key objectives of this study include:

1. Developing an optimized mix design for HSSCC using MSP, SF, and QS to enhance strength and durability while maintaining self-compactability.
2. Evaluating mechanical and durability properties under elevated temperatures to assess thermal resistance, spalling behavior, and residual strength.
3. Comparing the performance of HSSCC with High-Strength Vibrated Concrete (HSVC) to determine the advantages and limitations of each material in structural applications.
4. Utilizing Artificial Neural Networks (ANN) for predictive modeling of compressive strength, enabling accurate mix proportioning and reducing experimental trial requirements.

1.2 Research Significance

This study addresses critical gaps in the existing literature, particularly in understanding the high-temperature behavior of HSSCC. While previous research has explored the mechanical properties of SCC at ambient conditions, limited data exists on its performance under thermal exposure. Key aspects under investigation include:

- Spalling resistance—assessing whether HSSCC exhibits explosive spalling under rapid heating and identifying mitigation strategies.
- Thermal conductivity and stability—evaluating heat transfer properties and microstructural changes after exposure to elevated temperatures.
- Post-fire durability—analyzing residual strength and crack propagation patterns to determine the material's suitability for fire-resistant structures.

By integrating advanced materials and computational modeling, this research contributes to the development of high-performance concrete that meets both structural and durability demands in modern construction. The findings will provide valuable insights for engineers and researchers working on sustainable, high-strength, and fire-resistant concrete solutions.

2. 2.1 Materials

The selection of raw materials plays a crucial role in determining the fresh and hardened properties of High-Strength Self-Compacting Concrete (HSSCC). This study utilizes a combination of conventional and advanced materials to achieve optimal workability, mechanical strength, and durability. The following materials were used in the experimental investigation:

2.1.1 Cement

- Type: Ordinary Portland Cement (OPC) of 54-grade, complying with IS 12269 (2013) standards.
- Specific Gravity: 3.15
- Role in Mix: Acts as the primary binding agent, contributing to early and long-term strength development. The high-grade cement ensures better hydration and improved compressive strength.

2.1.2 Fine Aggregate

- Type: Natural river sand conforming to Zone-II as per IS 383 (2016).
- Specific Gravity: 2.47
- Fineness Modulus: 2.8 (medium-coarse grading)
- Role in Mix: Provides the necessary granular skeleton for workability and reduces voids in the concrete matrix. The use of Zone-II sand ensures a balanced particle size distribution, enhancing flowability and reducing water demand.

2.1.3 Coarse Aggregate

- Type: Mechanically crushed granite rock with a nominal size of 20 mm.
- Specific Gravity: 2.81
- Water Absorption: 0.8%
- Role in Mix: Provides structural stability and load-bearing capacity. The angular shape of crushed aggregates improves interlocking, while the 20 mm size ensures minimal blocking in highly reinforced sections.

2.1.4 Mineral Admixtures

To enhance the pozzolanic reactivity and durability of HSSCC, the following supplementary cementitious materials (SCMs) were incorporated:

Fly Ash (Class F)

- Source: Thermal power plant by-product.
- Specific Gravity: 2.2
- Role in Mix: Improves workability, reduces heat of hydration, and contributes to long-term strength through secondary pozzolanic reactions.

Ground Granulated Blast Furnace Slag (GGBS)

- Source: Industrial by-product from steel manufacturing.
- Specific Gravity: 2.9
- Role in Mix: Enhances durability, refines pore structure, and reduces permeability, making the concrete more resistant to chemical attacks.

Micro Silica (Silica Fume)

- Content: 8% by weight of cement
- Specific Gravity: 2.2
- Particle Size: ~0.1–0.5 µm (ultra-fine)
- Role in Mix: Fills micro-voids, increases packing density, and significantly boosts compressive strength due to its high pozzolanic reactivity.

2.1.5 Chemical Admixture

- Type: Glenium SP440G (Polycarboxylate Ether-based superplasticizer)
- Dosage: Optimized for desired flowability (typically 0.8–1.2% by weight of cement)
- Role in Mix: Ensures high workability and self-compactability without segregation by reducing water demand while maintaining low viscosity.

2.1.6 Fibers (For Hybrid Reinforcement)

To improve tensile strength, crack resistance, and post-cracking behavior, three types of fibers were used in hybrid combinations:

Coir Fibers (Natural Fiber)

- Length: 20–30 mm
- Diameter: 0.1–0.5 mm
- Role in Mix: Enhances ductility and impact resistance while providing eco-friendly reinforcement.

Kenaf Fibers (Natural Fiber)

- Length: 10–15 mm
- Tensile Strength: ~350 MPa
- Role in Mix: Improves flexural toughness and reduces shrinkage cracks.

Polypropylene Fibers (Synthetic Fiber)

- Length: 12–18 mm
- Dosage: 0.1–0.3% by volume
- Role in Mix: Prevents explosive spalling at high temperatures and enhances durability.

2.1.7 Water

- Type: Potable water conforming to IS 456 (2000) standards.
- Water-Cement Ratio (w/c): Maintained at 0.32–0.38 to ensure optimal hydration without compromising flowability.

2.1.8 Quarry Dust (QS) – Partial Replacement for Fine Aggregate

- Source: Crushed stone quarry waste.
- Specific Gravity: 2.6
- Role in Mix: Acts as a sustainable alternative to river sand, improving particle packing and reducing environmental impact.

2.2 Mix Design

The Nan Su method was adapted to treat Fly Ash and GGBS as separate additives. Key mix proportions for M70-grade HSSCC are summarized below:

Mix Type	Cement (kg/m³)	GGBS/FA (kg/m³)	Micro Silica (kg/m³)	Water (kg/m³)	Superplasticizer (L/m³)
HSSCCGGBS	452.22	208.19	41.28	158.19	11.51
HSSCCFA	447.91	148.54	42.51	185.17	12.58
HSVC	452	-	42.10	185.15	1.5

2.3 Methodology

1. Fresh Properties: Slump flow, compaction factor, and V-funnel tests assessed workability.
2. Mechanical Properties: Compressive, split tensile, and flexural strength tests at 7, 28, 56, and 90 days.
3. Durability Tests: Water permeability, sulfate/acid resistance, and thermal stability (up to 800°C).
4. ANN Modeling: Six input parameters (cement, admixtures, water, etc.) were used to predict compressive strength.

33.1 Fresh Properties of HSSCC

The fresh properties of High-Strength Self-Compacting Concrete (HSSCC) were evaluated through slump flow, compaction factor, and workability retention tests. The results demonstrated significant advantages over conventional High-Strength Vibrated Concrete (HSVC):

- Slump Flow Performance:
    - HSSCC with GGBS (HSSCC_{GGBS}) and HSSCC with Fly Ash (HSSCC_{FA}) ex hibited superior flowability, with slump values averaging 85 mm, indicating excellent deformability under self-weight.
    - In contrast, HSVC recorded a slump of 145 mm, requiring external vibration for proper compaction, which increases labor and equipment dependency.
    - The lower slump in HSSCC mixes is attributed to the optimized particle packing from supplementary cementitious materials (SCMs), which enhance stability without excessive water demand.
- Compaction Factor Analysis:
    - The compaction factor for HSSCC mixes ranged

between 0.85–0.95, confirming high workability and self-consolidation ability.

- Values closer to 1.0 indicate minimal voids and excellent compaction efficiency, crucial for dense reinforcement applications.
- The superior compaction behavior is due to the synergistic effect of micro silica (MSP) and superplasticizers, which reduce inter-particle friction and improve flow.

3.2 Mechanical Properties

3.2.1 Compressive Strength Development

- HSSCC_{GGBS} achieved a 28-day compressive strength of 58.55 MPa, outperforming HSVC (51.81 MPa) by ~13%.
- The enhanced strength is attributed to:
  - Pozzolanic reactivity of GGBS, which refines the microstructure and reduces capillary porosity.
  - Efficient particle packing due to the ultra-fine nature of silica fume (SF) and quarry dust (QS).
- HSSCC_{FA} also showed high early-age strength (45.2 MPa at 7 days), benefiting from the filler effect of fly ash.

3.2.2 Split Tensile Strength

- HSSCC_{FA} recorded a split tensile strength of 4.72 MPa, 16.8% higher than HSVC (4.04 MPa).
- The improvement is due to:
- Fiber reinforcement (coir, kenaf, and polypropylene), which bridges micro-cracks and enhances tensile resistance.
- Reduced micro-cracking from the pozzolanic action of fly ash.

3.2.3 Flexural Strength

- HSSCC_{GGBS} demonstrated a flexural strength of 8.72 MPa, ~20% higher than HSVC (7.25 MPa).
- The increase is linked to:
  - Hybrid fiber reinforcement, which improves post-cracking ductility.
  - Denser ITZ (Interfacial Transition Zone) due to GGBS and SF, reducing weak planes in the matrix.

3.3 Elevated Temperature Performance

3.3.1 Residual Strength After Exposure

- At 400°C, HSSCC_{GGBS} retained 70% of its original strength, while HSVC lost 40%.

- This is due to:
- Superior thermal stability of GGBS, which forms a more heat-resistant C-S-H gel.
- Polypropylene fibers, which melt at high temperatures, creating micro-channels that relieve vapor pressure and prevent explosive spalling.
  - At 800°C, HSSCC showed only 18.38% mass loss, compared to 22.15% for HSVC.

3.3.2 Microstructural Observations (SEM & XRD)

- SEM analysis revealed fewer micro-cracks in HSSCC after thermal exposure, confirming better durability.
- XRD patterns indicated stable hydration products (e.g., stratlingite) in HSSCC_{GGBS}, contributing to residual strength retention.

3.4 ANN-Based Strength Prediction

- An Artificial Neural Network (ANN) model was developed to predict compressive strength with high accuracy ($R^2 = 0.95$).
- Key Input Parameters:
  - Cement content, w/c ratio, %GGBS, %FA, fiber dosage.
- Advantages:
  - Reduces experimental trials by 30–40%.
  - Enables rapid optimization of mix designs for target strengths.

3.5 Durability Performance

3.5.1 Water Absorption & Permeability

- HSSCC_{GGBS} exhibite d 2.99% water absorption, nearly half that of HSVC (5.53%).
  - Reason: Denser microstructure from GGBS and SF reduces capillary pore connectivity.

3.5.2 Sulfate Resistance

- HSSCC mixes showed 25% better sulfate resistance than HSVC.

  Mechanism:
  - Aluminate phase control (GGBS reduces C3A content).
  - Pore refinement limits sulfate ion penetration.

3.5.3 Chloride Ion Penetration (RCPT Test)

- HSSCC_{GGBS} recorded <1000 Coulombs (ASTM C1202 "Very Low" permeability).
- HSVC showed >2000 Coulombs ("Moderate" permeability).

4. Conclusion

This study demonstrates that HSSCC incorporating MSP, SF, and QS achieves superior mechanical and durability properties compared to conventional HSVC. Key findings include:

1. HSSCCGGBS and HSSCCFA exhibit excellent workability and strength retention up to 400°C.
2. ANN models effectively predict compressive strength, aiding mix design optimization.
3. The use of industrial by-products (MSP, GGBS, FA) enhances sustainability.

Future work could explore hybrid fiber reinforcement and long-term durability under cyclic thermal loading. The research supports the adoption of HSSCC in high-performance structures, aligning with global sustainability goals.

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