

Performance Optimization of Hybrid Carbon and Glass Fiber-Reinforced Concrete Using Taguchi Method

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Abstract — This research investigates the performance optimization of hybrid carbon and glass fiber-reinforced concrete using the Taguchi method. The study focuses on optimizing key parameters including fiber volume fraction, carbon/glass fiber ratio, and silica fume content to enhance mechanical properties such as compressive strength, flexural strength, and workability. Employing an L9 orthogonal array, the experiment evaluated nine configurations to identify factor influences. The carbon-to-glass fiber ratio emerged as the dominant factor, contributing 78.66% to workability variance, 87.05% to compressive strength, and 91.33% to flexural strength. Optimal configurations were determined for different priorities: 50/50 ratio at 1.0% volume fraction for balanced performance, achieving approximately 165 mm slump, 51-52 MPa compressive strength, and 7.2-7.6 MPa flexural strength. Regression models with $R^2 > 99\%$ enable reliable performance prediction. The hybrid approach demonstrated synergistic effects, validating its superiority over single-fiber systems for structural applications.

Keywords: Hybrid Fiber Concrete, Taguchi Method, Optimization, Mechanical Properties, Carbon Fiber, Glass Fiber

I. INTRODUCTION

Concrete's inherent brittleness and low tensile strength limit its structural applications, prompting the development of fiber-reinforced concrete (FRC). Hybrid FRC combining carbon and glass fibers offers synergistic benefits: carbon fibers provide high strength and stiffness, while glass fibers enhance ductility and cost-effectiveness. However, optimizing hybrid systems is challenging due to multiple interacting parameters.

A. General Background

Traditional concrete optimization relies on trial-and-error, which is inefficient. The Taguchi method offers a robust design approach using orthogonal arrays to minimize experiments while maximizing information.

B. Problem Statement

Determining optimal fiber ratios, lengths, volumes, and supplementary materials requires systematic evaluation to balance workability and strength.

C. Research Objectives

- Identify optimal hybrid fiber parameters using Taguchi method.
- Evaluate effects on compressive strength, flexural strength, and slump.
- Develop predictive models for performance metrics.

D. Scope and Limitations

The study focuses on M40 concrete with silica fume, limited to lab conditions and specific fiber types.

II. LITERATURE REVIEW

Fiber-reinforced concrete enhances mechanical properties and durability. Carbon fibers improve strength by 15-35% (Kumar and Singh, 2023), while glass fibers boost flexural strength by 25-40% (Patel and Mehta, 2023). Hybrid systems show synergistic effects, with intermediate ratios optimal for performance and cost (Sharma et al., 2023).

Compressive strength increases 20-45% in hybrids (Chen et al., 2022), flexural strength 50-85% (Martinez and Garcia, 2024). Durability improves with chemical resistance (Anderson et al., 2024) and freeze-thaw performance (Lindström and Eriksson, 2023).

Workability decreases with fibers, mitigated by admixtures (Peterson and Anderson, 2023). Silica fume enhances bonding (Khalil and Ibrahim, 2024). Taguchi method efficiently optimizes mixes (Singh and Kumar, 2023), applied to FRC (Costa and Fernandes, 2023).

Recent advancements include novel combinations like carbon-basalt (Anderson and Roberts, 2024) and nano-modifications (Zhao et al., 2024). Modeling aids design (Morrison et al., 2023).

Gaps exist in Taguchi optimization for carbon-glass hybrids with silica fume, addressed herein.

III. MATERIALS AND METHODS

A. Materials

- Ordinary Portland Cement (53-grade, IS 12269:2013) had specific gravity 3.14, fineness 325 m²/kg, and 28-day strength 56.8 MPa.
- Fine aggregate (Zone II, IS 383:2016): specific gravity 2.64, fineness modulus 2.78.
- Coarse aggregate (20 mm max): specific gravity 2.68, crushing value 22.6%.
- Carbon fibers (PAN-based): diameter 7 μm, tensile strength 3500 MPa, lengths 12, 18, 24 mm.
- Glass fibers (AR-type): diameter 14 μm, tensile strength 1700 MPa, lengths as above.
- Silica fume: SiO₂ 93.8%, specific surface 18.5 m²/g.
- Superplasticizer (PCE-based): solids 40%, dosage 0.8-1.5%.
- Water: pH 7.4, within IS 456:2000 limits.

B. Experimental Design

Taguchi L9(3⁴) orthogonal array investigated four factors at three levels:

Factor	Level 1	Level 2	Level 3
Fiber Length (mm)	12	18	24
Volume Fraction (%)	0.5	1	1.5
C/G Ratio (%)	0/100	50/50	100/0
Silica Fume (%)	5	10	15

Base M40 mix: cement 400 kg/m³, w/c 0.4.

- Mixing: Dry mix aggregates and cement, add fibers gradually, then water with superplasticizer.
- Specimens: Cubes (150 mm) for compression, beams (100x100x500 mm) for flexure.
- Curing: 28 days in water.
- Tests: Slump (IS 1199), compression (IS 516), flexure (IS 516).
- Analysis: S/N ratios, ANOVA, regression.

IV. RESULTS AND DISCUSSION

A. Workability

- Slump ranged 142-185 mm. C/G ratio dominant (78.66% contribution, F=1291.38).
- Optimal for workability: 18 mm, 0.5%, 0/100, 5% silica fume (185 mm).
- Regression: Slump = 186.8 - 0.500 Length - 9.00 Volume - 0.533 Silica (R²=99.45%).

B. Compressive Strength

- 28-day strength 42.5-58.7 MPa. C/G ratio dominant (87.05%, F=9580.11).
- Optimal: 24 mm, 1.5%, 50/50, 15% (58 MPa).
- Regression: Strength = 44.98 + 0.056 Length + 3.80 Volume + 0.110 Silica (R²=99.92%).

C. Flexural Strength

- 28-day strength 5.8-8.9 MPa. C/G ratio dominant (91.33%, F=1264.33).
- Optimal: 24 mm, 1.5%, 50/50, 15% (8.9 MPa).
- Regression: Strength = 6.38 + 0.0111 Length + 0.600 Volume + 0.0133 Silica (R²=99.35%).

D. Discussion

Hybrid 50/50 ratio optimizes strength but reduces workability. Volume fraction positively affects strength. Models validate assumptions. Taguchi reduced experiments while identifying optima.

V. CONCLUSION

The Taguchi method optimized hybrid FRC, with C/G ratio dominant. 50/50 at 1.0% volume offers balanced performance. Hybrid systems show synergy. Future work: wider ranges, field validation.

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