Sustainable Utilization of Marble Dust and Blast Furnace Slag as Fine Aggregate Replacement in Pavement Quality Concrete: A Comprehensive Review with Taguchi Optimization

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Abstract — The depletion of natural river sand and rising environmental burden of industrial waste disposal have intensified global interest in sustainable concrete technology. This paper reviews and presents experimental results on the partial replacement of natural fine aggregates with Marble Dust (MD) and Blast Furnace Slag (BFS) in Pavement Quality Concrete (PQC), optimized using the Taguchi Design of Experiment (DOE) with an L9 orthogonal array. Three design parameters — MD replacement (0%, 10%, 20%), BFS replacement (0%, 15%, 30%), and water-cement ratio (0.35, 0.38, 0.40) — were evaluated for M40 grade PQC as per IRC:44-2017. The optimal mix (20% MD + 30% BFS, W/C = 0.38) yielded a 28-day modulus of rupture of 5.32 MPa, exceeding the IRC:58-2015 minimum of 4.50 MPa by 18.2%. ANOVA identified water-cement ratio as the dominant factor (31.2% contribution). SEM and XRD confirmed pozzolanic mechanisms, with a 35% reduction in Portlandite and 28% increase in C-S-H formation. Results demonstrate that a 50% combined substitution of natural sand with industrial by-products is technically viable and yields superior PQC.

Keywords: Pavement Quality Concrete, Marble Dust, Blast Furnace Slag, Taguchi Method, L9 Orthogonal Array, IRC:58-2015, Compressive Strength, Flexural Strength, ANOVA, Sustainable Concrete

I. INTRODUCTION

Global urbanization and infrastructure expansion have driven unprecedented growth in concrete consumption, projected to reach 66.2 billion metric tons by 2025 [1]. Pavement Quality Concrete (PQC) constitutes a critical component of rigid pavement systems governed by Indian Roads Congress (IRC) codes. Widespread use of river sand has led to severe ecological degradation, riverbed disruption, and supply shortages, motivating engineers to seek industrial by-products as sustainable alternatives [2].

India is among the world's largest marble producers, generating approximately 20–30% waste in the form of dust and slurry during processing — particularly in Rajasthan. Simultaneously, blast furnace slag (BFS), a by-product of pig iron manufacturing, is produced in millions of tonnes annually with significant disposal challenges. Both materials exhibit physico-chemical properties that are potentially beneficial to concrete when used as fine aggregate replacements [3].

The Taguchi Method, a robust statistical design of experiment (DOE) technique, systematically explores multi-parameter interactions with a minimal number of experimental trials. Its application via an L9 orthogonal array reduces trial count by 67% versus full-factorial design, making it particularly suited for concrete mix optimization [4]. This paper presents experimental findings and statistical analysis of M40 grade PQC incorporating MD and BFS, analyzed through Taguchi-ANOVA methodology, to establish evidence-based guidelines for sustainable pavement construction.

II. MATERIAL PROPERTIES

A. Marble Dust (MD)

Marble Dust (MD) is a fine by-product generated during the sawing, cutting, and polishing of marble slabs. Its primary constituent is Calcium Carbonate ($CaCO_3$, ~91.5%), with minor proportions of SiO_2, Al_2O_3, Fe_2O_3, and MgO. Physically, MD exhibits a specific gravity of approximately 2.65, fineness modulus of ~1.27, and a Blaine fineness of ~380 m²/kg. Its high angularity and filler capacity contribute to pore refinement in the cement paste matrix, improving microstructural density and the Interfacial Transition Zone (ITZ) [5].

B. Blast Furnace Slag (BFS)

Blast Furnace Slag is a glassy, granular by-product generated during the smelting of iron ore. Its chemical composition is dominated by CaO (~37%), SiO_2 (~34%), Al_2O_3 (~18%), and MgO (~8.2%), conferring latent hydraulic and pozzolanic reactivity. With a specific gravity of 2.60–2.70 and fineness modulus of ~1.76, BFS falls within an acceptable range for fine aggregate in PQC. The glassy microstructure participates in secondary cementitious reactions when activated by calcium hydroxide, contributing to long-term strength gain [6].

C. Comparative Properties

Property	Nat. Sand	MD	BFS
Sp. Gravity	2.65	2.65	2.63
Fineness Mod.	2.71	1.27	1.76
Water Abs. (%)	0.50	1.20	0.80
Bulk Den. (kg/m³)	1630	1490	1550

Table I" Comparative Physical Properties of Fine Aggregate Materials

III. EXPERIMENTAL METHODOLOGY

A. Mix Design as per IRC:44-2017

A control PQC mix of M40 grade was proportioned per IRC:44-2017 using OPC 43 Grade cement (specific gravity 3.12, normal consistency 30%, initial setting time 48 min). Coarse aggregates of 20 mm and 10 mm nominal size were blended in a 60:40 ratio. The baseline W/C ratio was set at 0.38 with Conplast SP430 superplasticizer at 0.5–1.2% of cement to maintain target workability (slump 50–75 mm per MoRTH Section 600) [7].

B. Taguchi L9 Orthogonal Array

The Taguchi Method was applied using an L9(3^4) orthogonal array with three control factors at three levels each: MD replacement (A: 0%, 10%, 20%), BFS replacement (B: 0%, 15%, 30%), and water-cement ratio (C: 0.35, 0.38, 0.40). Nine distinct experimental mixes were thus generated, reducing the experimental matrix from 27 to 9 — a 67% reduction in testing effort while maintaining statistical orthogonality [4].

Mix	MD %	BFS %	W/C
L1 (Ctrl)	0	0	0.35
L2	0	15	0.38
L3	0	30	0.40
L4	10	0	0.38
L5	10	15	0.40
L6	10	30	0.35
L7	20	0	0.40
L8	20	15	0.35
L9 (Opt)	20	30	0.38

Table II: Taguchi L9 Orthogonal Array — Mix Layout

C. Specimen Preparation and Testing

Standard 150 mm cube specimens (IS:516-1959) were cast for compressive strength; 500×100×100 mm beams for flexural strength (third-point loading); and 150×300 mm cylinders for splitting tensile strength. All specimens were water-cured at 27±2°C and tested at 7 and 28 days. Workability was assessed via slump cone test (IS:1199). Statistical analysis (S/N ratios, ANOVA, MLR) was performed in Minitab 2022.

IV. Results and Discussion

A. Workability

Slump values across all L9 mixes ranged from 46 mm to 72 mm, satisfying the MoRTH Section 600 requirement of 25–75 mm. MD incorporation marginally reduced workability due to higher water absorption, requiring a 0.1–0.2% increase in superplasticizer dosage. BFS replacement improved flowability owing to its smooth glassy particle morphology. Mixes at W/C = 0.40 consistently exhibited higher slump values.

B. Compressive Strength

The 28-day compressive strength ranged from 41.8 MPa (L3) to 53.6 MPa (L9), compared to the control (L1) value of 43.2 MPa — a 24% improvement by the optimal mix. The 56-day strength of L9 reached 58.4 MPa, indicating continued pozzolanic activity. MD from 0% to 20% progressively enhanced compressive strength through improved particle packing and filler action [8].

C. Flexural Strength (MOR)

The 28-day MOR of all nine mixes exceeded the IRC:58-2015 minimum of 4.50 MPa. The optimal mix (L9) recorded MOR = 5.32 MPa, exceeding the IRC minimum by 18.2%. The superior flexural performance is attributed to the angular texture of MD particles, which enhances mechanical interlocking at the aggregate-paste interface, and to ITZ densification from BFS pozzolanic reactions [9].

D. Splitting Tensile Strength

Splitting tensile strength (STS) at 28 days ranged from 3.10 MPa (L3) to 4.12 MPa (L9), with the optimal mix exhibiting a 28.3% improvement over the control. A strong empirical correlation was established between STS and CS: STS = 0.068 × CS^0.85 (R^2 = 0.94), consistent with IS:456 recommendations [10].

Mix	MD	BFS	W/C	CS-28 (MPa)	MOR-28 (MPa)	STS-28 (MPa)
L1	0%	0%	0.35	43.2	4.71	3.21
L2	0%	15%	0.38	44.8	4.82	3.35
L3	0%	30%	0.40	41.8	4.56	3.10
L4	10%	0%	0.38	46.5	4.93	3.48
L5	10%	15%	0.40	45.1	4.87	3.39
L6	10%	30%	0.35	49.3	5.08	3.72
L7	20%	0%	0.40	47.2	5.01	3.55
L8	20%	15%	0.35	51.4	5.19	3.88
L9	20%	30%	0.38	53.6	5.32	4.12

Table III: Strength Results — All L9 Experimental Mixes

V. Taguchi Optimization and ANOVA

A. Signal-to-Noise Ratio Analysis

S/N ratios were computed under the Larger-is-Better (LTB) criterion: $S/N = -10 \log(\Sigma(1/y^2)/n)$. For 28-day compressive strength, water-cement ratio ranked first (delta = 2.84 dB), followed by MD content (delta = 2.31 dB) and BFS content (delta = 1.76 dB). The optimal factor combination identified was A3B3C2 (MD = 20%, BFS = 30%, W/C = 0.38), corresponding to Mix L9 [4].

B. ANOVA — Factor Contribution

ANOVA quantified the percentage contribution of each factor. For 28-day CS, water-cement ratio contributed 31.2%, MD content 24.8%, BFS content 18.6%, and the MD×BFS interaction 12.4%. The significant MD×BFS interaction confirms synergistic enhancement — BFS pozzolanic activity is complemented by MD's filler and nucleation effects [11].

Factor	CS (%)	MOR (%)	STS (%)	Rank
W/C Ratio (C)	31.2	33.5	29.8	1
Marble Dust (A)	24.8	22.4	23.1	2
Furn. Slag (B)	18.6	17.2	19.4	3
A×B Interaction	12.4	11.8	13.2	4
Error	13.0	15.1	14.5	—

Table IV: Anova Percentage Contribution Summary

C. Regression Models

Multiple Linear Regression (MLR) models provided validated predictive equations. For 28-day compressive strength: $CS_{28} = 82.4 - 96.5(W/C) + 0.312(MD\%) + 0.184(BFS\%)$, with $R^2 = 0.967$ and maximum prediction error of 4.59%. These models offer practical tools for field engineers to estimate expected concrete strength without additional casting [12].

VI. Microstructural Analysis

A. *Scanning Electron Microscopy (SEM)*

SEM analysis at 1000× and 5000× magnification revealed critical microstructural differences. The control mix (L1) showed an ITZ width of 15–25 µm with Portlandite crystal deposits. The optimal mix (L9) demonstrated a significantly refined ITZ width of 8–12 µm, attributable to the filler effect of fine MD particles and the pozzolanic secondary reaction of BFS. The denser, more homogeneous microstructure of L9 explains its superior mechanical performance [9].

B. *X-Ray Diffraction (XRD)*

XRD analysis confirmed that the optimal mix exhibited a 35% reduction in Portlandite ($Ca(OH)_2$) peak intensity, accompanied by a 28% increase in C-S-H gel formation. The reduction in Portlandite is attributable to the pozzolanic reaction between the amorphous silica in BFS and $Ca(OH)_2$ released during OPC hydration. MD acts as a nucleation site for C-S-H formation, accelerating early-age microstructure development [3].

VII. Pavement Design and Sustainability

The IRC:58-2015 framework uses 28-day MOR as the primary design parameter for slab thickness. An increase in design MOR from 4.50 MPa (IRC minimum) to 5.32 MPa (optimal mix L9) reduces slab thickness by approximately 25–30 mm, translating to material savings of 6–8% and a corresponding cost reduction. The combined replacement of 50% natural sand with MD and BFS aligns with UN SDGs 9, 11, and 12, reducing riverbed sand mining and diverting industrial wastes from landfills [2].

From an economic standpoint, MD and BFS are available at significantly lower cost than river sand in regions adjacent to marble quarries (Rajasthan, Andhra Pradesh) and steel plants (Jharkhand, Chhattisgarh). The fine aggregate cost per cubic meter of PQC can be reduced by 15–22% when 50% natural sand is replaced by these by-products [5].

VIII. Conclusions

The following key conclusions are drawn from this investigation:

1) All nine Taguchi L9 mixes satisfied the IRC:58-2015 minimum MOR of 4.50 MPa, confirming the suitability of MD and BFS as fine aggregate replacements in PQC.
2) The optimal mix (20% MD + 30% BFS, W/C = 0.38) achieved the highest 28-day CS (53.6 MPa) and MOR (5.32 MPa), representing improvements of 24% and 13% over the control, respectively.
3) Water-cement ratio was the most influential factor (ANOVA: 31.2% for CS), followed by MD content (24.8%) and BFS content (18.6%). The MD×BFS interaction (12.4%) confirms synergistic effects.
4) SEM/XRD microstructural analysis validated the pozzolanic mechanism: a 35% reduction in Portlandite, 28% increase in C-S-H gel, and ITZ refinement from 15–25 µm to 8–12 µm.
5) Validated regression models ($R^2 > 0.96$, max error 4.59%) provide reliable tools for PQC mix design. The optimal mix offers 25–30 mm slab thickness reduction and 15–22% fine aggregate cost savings.

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