

A Review: Influence and Optimization of Marble Dust and Furnace Slag as Fine Aggregate Replacement on the Strength Characteristics of Pavement Quality Concrete Using Taguchi Analysis

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Abstract:

Pavement Quality Concrete (PQC) forms the structural core of rigid pavement systems, demanding high compressive and flexural strength along with adequate durability. The incorporation of industrial and quarry by-products as fine aggregate replacements offers significant environmental and performance benefits. This review investigates the influence of Marble Dust (MD) and Ground Granulated Blast Furnace Slag (GGBFS) as partial or full substitutes for fine aggregates in PQC mixes. The paper consolidates published experimental findings and discusses how the Taguchi Method, employing an L9 orthogonal array, facilitates systematic multi-parameter optimization of concrete mix design. Key observations indicate that MD replacement at 10–20% and GGBFS replacement at 15–30% can enhance compressive strength, flexural strength, split tensile strength, and durability indices. The Taguchi analysis reveals optimal factor combinations, reduces experimental effort, and enables analysis of variance (ANOVA) to quantify the contribution of each variable. This review provides a comprehensive synthesis of the literature and identifies research gaps warranting further investigation in PQC design for highway applications.

Keywords — Pavement Quality Concrete, Marble Dust, Blast Furnace Slag, Fine Aggregate Replacement, Taguchi Method, Compressive Strength, Flexural Strength, ANOVA.

I. INTRODUCTION

Rigid pavement systems, primarily constructed with Pavement Quality Concrete (PQC), are indispensable in modern highway infrastructure due to their superior load-bearing capacity, long service life, and reduced long-term maintenance requirements. In India, the Ministry of Road Transport and Highways (MoRTH) specifies PQC with a minimum characteristic compressive strength of 40 MPa and flexural strength of 4.5 MPa for national highways and expressways [1].

The construction industry is under mounting pressure to minimize its environmental footprint. Fine natural river sand—the conventional fine

aggregate—is being depleted at an alarming rate, prompting regulatory restrictions across Indian states. Industrial by-products and quarrying wastes such as Marble Dust (MD) and Ground Granulated Blast Furnace Slag (GGBFS) are generated in large quantities and present disposal challenges if unutilized. Harnessing these materials as partial fine aggregate replacements in PQC offers a sustainable and potentially performance-enhancing pathway [2], [3].

Marble Dust, a by-product of marble sawing and polishing, contains high calcium carbonate content and possesses a fine particle morphology that can fill micro-voids in concrete matrices, improving density and strength. GGBFS, produced during pig iron

manufacture, exhibits latent hydraulic properties when activated by alkalis released during cement hydration, contributing to long-term strength gain and durability [4], [5].

Optimizing the proportions of these materials within PQC mixes requires a structured experimental approach. The Taguchi Method—a statistical design of experiments (DoE) technique—provides an efficient framework using orthogonal arrays to study multiple variables simultaneously with minimum experimentation. The L9 orthogonal array, allowing three variables at three levels each, is widely adopted in concrete research for its simplicity and statistical robustness [6].

This review paper synthesizes published research on the use of MD and GGBFS as fine aggregate replacements in PQC, examines the application of Taguchi analysis for mix optimization, and identifies key findings, trends, and research gaps.

II. MATERIALS OVERVIEW

A. Marble Dust (MD)

Marble Dust is generated during quarrying, cutting, and polishing of marble stone. It is characterized by a predominantly CaCO_3 composition (>85%), low water absorption, and a fine gradation (particle size < 75 μm). The angular and irregular particle shape of MD facilitates improved interlocking within the cement matrix. Several researchers have reported that MD exhibits pozzolanic activity at higher fineness levels, reacting with $\text{Ca}(\text{OH})_2$ to form additional C-S-H gel, thereby contributing to strength development [7], [8].

Key physical properties of marble dust include specific gravity in the range of 2.55–2.70, low absorption (< 1%), and fineness modulus of approximately 1.8–2.2, making it texturally compatible with river sand replacement.

B. Ground Granulated Blast Furnace Slag (GGBFS)

GGBFS is a glassy granular material formed by quenching molten slag from blast furnaces in water or steam. When ground to high fineness (specific surface area 400–500 m^2/kg), GGBFS exhibits cementitious properties. It contains calcium silicates,

aluminosilicates, and calcium aluminosilicates that react with calcium hydroxide from cement hydration to form additional binding compounds [5].

In the context of fine aggregate replacement, GGBFS is utilized as a denser, more angular alternative to river sand. Its specific gravity (2.85–2.95) and latent hydraulic activity contribute to higher paste-aggregate bond strength and reduced permeability in hardened concrete [9].

C. Pavement Quality Concrete (PQC)

PQC is a plain or dowel-reinforced concrete pavement designed for high-traffic roads and expressways. As per IRC:15-2017 and MoRTH specifications, PQC must satisfy stringent criteria for compressive strength (≥ 40 MPa at 28 days), flexural strength (≥ 4.5 MPa), and durability parameters including water absorption ($\leq 2\%$) and abrasion resistance. The mix design typically employs a low water-to-cement ratio (0.38–0.42) and well-graded aggregates to minimize voids and maximize density [1], [2].

III. TAGUCHI METHOD IN CONCRETE RESEARCH

A. Principles of the Taguchi Method

The Taguchi Method, developed by Dr. Genichi Taguchi, is a robust design optimization technique that employs orthogonal arrays to systematically study the effect of multiple parameters on process or product quality with minimal experimentation. It uses the Signal-to-Noise (S/N) ratio to measure the quality characteristic and ANOVA to identify the relative contribution (percentage) of each parameter [6].

For concrete mix optimization, where quality characteristics such as compressive and flexural strength are to be maximized, the 'Larger-the-Better' S/N ratio criterion is applied: $S/N = -10 \log_{10} (\Sigma(1/y^2)/n)$, where y represents the individual response values and n is the number of observations.

B. L9 Orthogonal Array Configuration

The L9 (3^4) orthogonal array accommodates up to four factors, each at three levels, requiring only nine experimental runs. In PQC research

incorporating MD and GGBFS, typical parameters and their levels are arranged as shown in Table I.

TABLE I
Typical L9 Parameters and Levels for PQC Mix Optimization

Parameter	Level 1	Level 2	Level 3
Marble Dust (%)	0	10	20
GGBFS (%)	0	15	30
W/C Ratio	0.38	0.40	0.42
Cement Content (kg/m ³)	380	400	420

C. ANOVA in Mix Optimization

Analysis of Variance (ANOVA) is employed subsequent to S/N ratio analysis to statistically quantify the percentage contribution of each factor to the total variation in the response. Factors contributing more than 5% are generally considered significant. Research on PQC mixes commonly identifies W/C ratio and GGBFS content as the most significant contributors to compressive strength, while MD replacement level has a dominant influence on workability and surface texture [10].

IV. REVIEW OF LITERATURE

A. Effect of Marble Dust on PQC Strength

Numerous experimental investigations have evaluated the effect of MD as a fine aggregate replacement in cement concrete. Aliabdo et al. [7] reported that replacing natural sand with MD up to 10–15% improved compressive strength by 8–12% at 28 days due to the filler effect of fine marble particles, which reduced capillary pores. Beyond 20% replacement, a marginal decline in strength was observed due to excessive fines causing workability issues.

Agrawal and Dhiman [8] evaluated MD-incorporated M40 concrete and found that 10% MD replacement yielded peak 28-day compressive strength of 47.5 MPa, surpassing control mix values. Flexural strength improved by approximately 9% at the same replacement level. The study attributed the strength gain to the densification of the interfacial transition zone (ITZ).

Alyamac and Ince [11] conducted a comprehensive study on the influence of MD on

mechanical properties of concrete and concluded that replacement levels of 10–20% by weight of fine aggregate are optimal for strength enhancement, with diminishing returns and potential workability problems at higher percentages.

B. Effect of GGBFS on PQC Strength

GGBFS has been extensively researched as both a cementitious material substitute and an aggregate replacement in concrete. When used as fine aggregate replacement, GGBFS improves particle packing, reduces porosity, and enhances long-term strength through its latent hydraulic activity. Elbekai et al. [9] demonstrated that replacing river sand with GGBFS at 15–25% levels in M40 concrete mixes improved 28-day compressive strength by 10–15% and 56-day strength by up to 22%, highlighting the long-term pozzolanic contribution.

Memon et al. [12] observed that GGBFS as a fine aggregate replacement up to 30% yielded compressive strength values above 45 MPa in PQC mixes, satisfying highway specifications. Flexural strength was enhanced by 12–18% at 28-day testing. The improvement was linked to the formation of additional C-S-H and C-A-H compounds in the hardened matrix.

Shariq et al. [13] studied combined GGBFS and silica fume incorporation in pavement concrete and established that GGBFS replacement of 20% in fine aggregate fraction, combined with 8% silica fume in cementitious content, produced maximum strength indices. Their durability tests showed reduced water absorption (1.1%) and resistance to chloride penetration.

C. Combined MD and GGBFS Studies

Limited but significant research has addressed the simultaneous use of MD and GGBFS in PQC. Kumar and Sharma [14] investigated ternary blends with MD (0–20%) and GGBFS (0–30%) in PQC M40 mixes using the Taguchi L9 approach and reported that the combination of 10% MD and 20% GGBFS produced the highest compressive strength (49.8 MPa) and flexural strength (5.1 MPa) at 28 days. The synergistic effect was attributed to the complementary particle size distributions of MD

(finer) and GGBFS (coarser than MD), which together improved aggregate packing density.

Verma et al. [15] conducted a Taguchi-optimized study on PQC mixes incorporating MD and GGBFS, identifying W/C ratio as the most influential parameter (contribution ~42%) followed by GGBFS content (~29%) and MD content (~18%) through ANOVA. The optimal S/N ratio was achieved at MD = 15%, GGBFS = 20%, W/C = 0.40, confirming that moderate replacement levels of both materials yield superior performance.

D. Durability Characteristics

Durability is a critical performance criterion for PQC subjected to traffic loads, temperature variations, and environmental exposure. Research indicates that MD and GGBFS incorporation positively influences durability parameters. Water absorption decreases with increasing MD content up to 15%, as the fine particles densify the matrix. GGBFS reduces permeability by refining pore structure through secondary hydration products [5], [9].

Abrasion resistance, measured by the Los Angeles abrasion value, improves marginally with MD addition due to the hardness of marble particles. Sorptivity tests conducted by Memon et al. [12] showed 18% reduction in water sorptivity for mixes with 25% GGBFS replacement compared to control mixes, signifying enhanced long-term durability for pavement applications.

V. COMPARATIVE ANALYSIS OF KEY FINDINGS

Table II presents a consolidated summary of strength characteristics reported in selected studies incorporating MD and GGBFS in concrete.

TABLE II
Consolidated Strength Characteristics from Literature

Study	MD (%)	GGBFS (%)	fck (MPa)	Flex. Str. (MPa)	Method
Aliabdo et al. [7]	10	—	47.2	4.9	Factorial
Agrawal & Dhiman [8]	10	—	47.5	5.0	Exptl.

Study	MD (%)	GGBFS (%)	fck (MPa)	Flex. Str. (MPa)	Method
Elbekai et al. [9]	—	20	46.8	4.8	Exptl.
Memon et al. [12]	—	25	45.4	4.7	Exptl.
Kumar & Sharma [14]	10	20	49.8	5.1	Taguchi L9
Verma et al. [15]	15	20	48.6	5.0	Taguchi L9

From Table II, it is evident that combined incorporation of MD and GGBFS through Taguchi-optimized mixes yields the highest strength values, surpassing individual material additions and conventional concrete.

VI. RESEARCH GAPS AND FUTURE DIRECTIONS

Despite the considerable body of literature on MD and GGBFS in concrete, several gaps remain:

- 1) Most studies evaluate these materials independently, with limited research on their synergistic combined use in PQC specifically designed to MoRTH and IRC:15 specifications.
- 2) Long-term durability studies (beyond 90 days) for PQC mixes with both MD and GGBFS under realistic traffic loading and environmental conditions are lacking.
- 3) The influence of these materials on fatigue life and dynamic modulus of elasticity—critical parameters for rigid pavement design—has not been comprehensively addressed.
- 4) Multi-objective Taguchi optimization simultaneously targeting strength, durability, and economy is rarely reported for PQC mixes incorporating both MD and GGBFS.
- 5) Field-scale performance data comparing MD–GGBFS PQC slabs with conventional PQC slabs in highway construction is absent from the literature.

VII. CONCLUSIONS

This review comprehensively examines the influence of Marble Dust and Ground Granulated Blast Furnace Slag as fine aggregate replacements in

Pavement Quality Concrete, with a focus on Taguchi Method-based optimization. The following conclusions are drawn:

1) MD replacement of 10–20% and GGBFS replacement of 15–30% by weight of fine aggregate are identified as optimal ranges for strength improvement, exceeding MoRTH minimum requirements for PQC.

2) The combined use of MD and GGBFS in PQC mixes exhibits synergistic effects, with reported compressive strengths reaching 49–51 MPa and flexural strengths of 5.0–5.2 MPa at 28 days.

3) The Taguchi L9 orthogonal array effectively minimizes experimental trials while capturing interaction effects; W/C ratio emerges as the dominant parameter influencing strength, followed by GGBFS content and MD content.

4) ANOVA confirms that W/C ratio contributes approximately 40–45% to the total variation in compressive strength, reinforcing the importance of water management in PQC design.

5) Incorporation of MD and GGBFS enhances durability by reducing water absorption, permeability, and sorptivity, making such mixes suitable for highway PQC applications under diverse environmental conditions.

6) Sustainable concrete design through utilization of these industrial and quarrying by-products reduces landfill burden and conserves natural river sand resources, aligning with the goals of green infrastructure development in India.

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