

Performance Evaluation of Fired Clay Bricks Incorporating Waste Marble Powder as a Sustainable Partial Replacement for Clay

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Abstract

The rapid growth of the marble processing industry generates significant quantities of waste marble powder (WMP), leading to environmental concerns such as land degradation, air pollution, and groundwater contamination. Simultaneously, conventional fired clay brick production relies heavily on natural clay resources, raising sustainability concerns. This study investigates the feasibility of utilising WMP as a partial replacement for clay in fired brick manufacturing to promote waste valorisation and sustainable construction. Waste marble powder collected from processing units in Bengaluru, India, was characterised using Energy-Dispersive X-ray Spectroscopy and scanning electron microscopy (SEM). Brick specimens were produced with WMP replacement levels ranging from 0% to 25% by weight of clay and fired under controlled laboratory conditions. The physical, mechanical, and durability properties of the bricks, including compressive strength, water absorption, apparent porosity, initial rate of absorption (IRA), bulk density, and efflorescence, were evaluated according to relevant standards. Environmental safety was assessed through the Toxicity Characteristic Leaching Procedure (TCLP). The results indicated that incorporating 15% WMP (CM15) produced the optimum performance. The compressive strength increased to 15.92 MPa, representing a 34.3% improvement over the control brick (11.85 MPa), while water absorption, apparent porosity, and IRA decreased to 12.11%, 29.87%, and 0.10 g/min/cm², respectively. Bulk density increased slightly to 2.05 g/cc, reflecting enhanced particle packing and densification. TCLP results confirmed that heavy metal concentrations remained well below regulatory limits. The improvements were attributed to the microfiller effect and fluxing behaviour of carbonate minerals present in WMP. The study demonstrates that up to 15% WMP can be effectively utilised in fired clay bricks, producing sustainable, environmentally safe, and structurally suitable masonry units while reducing waste disposal and conserving natural clay resources.

Keywords: Waste marble powder; Fired clay bricks; Compressive strength; Sustainability; Leachability; Microstructure; Circular economy; Sustainable construction materials

1. Introduction

India ranks as the third-largest global producer of marble, with the state of Rajasthan alone accounting for approximately 95% of national output through more than 1,200 processing units and 3,600 quarries. This extensive industrial activity generates an estimated 5–6 million metric tons of marble waste annually, predominantly in the form of slurry and fine powder (Ministry of Industry, Energy and Mines, Government

of India). Improper disposal of this waste leads to land occupation, dust pollution affecting air quality and human health, and potential contamination of soil and water bodies. Concurrently, the Indian brick manufacturing sector, driven by rapid urbanisation and housing demand, consumes vast quantities of fertile clay, contributing to resource depletion, topsoil loss, and significant greenhouse gas emissions from kiln firing.

The incorporation of industrial by-products into fired clay bricks has emerged as a promising strategy for waste valorisation and resource conservation. Previous investigations have demonstrated the technical feasibility of using waste marble powder (WMP) in brick production. Bilgin et al. (2012) reported that up to 80% marble dust could be added while maintaining acceptable physico-mechanical properties, with optimal performance observed at elevated firing temperatures. Sutcu et al. (2015) produced lightweight bricks with 0–35% WMP, resulting in reduced thermal conductivity and density, but at the expense of compressive strength at higher dosages. Sufian et al. (2021) and subsequent studies confirmed that moderate replacements (typically 10–20%) enhance densification through the filler and fluxing effects of calcite while reducing production costs and environmental footprint. However, comprehensive evaluations that integrate mechanical performance, durability indicators, microstructural mechanisms, and environmental safety (particularly the leachability of heavy metals) for Indian-sourced marble powder remain limited, especially under standardised Indian testing protocols.

This study addresses this gap by systematically investigating the performance of fired clay bricks incorporating 0–25% WMP by weight as a partial clay replacement. The specific objectives were to: (i) characterize the physico-chemical and mineralogical properties of locally sourced WMP; (ii) evaluate the influence of WMP content on compressive strength, water absorption, porosity, initial rate of absorption, density, and efflorescence; (iii) identify the optimum replacement level through experimental trends and mechanistic interpretation; (iv) assess microstructural evolution using SEM; and (v) verify environmental safety via TCLP testing on the optimal mix. The outcomes are intended to support evidence-based adoption of WMP in sustainable brick manufacturing, contributing to circular economy objectives and reduced environmental burdens associated with both marble waste disposal and conventional clay extraction.

2. Materials and Methods

2.1. Materials

The base material was a locally available plastic clay sourced from Tavarekere, Bengaluru, Karnataka, India, selected for its suitability in traditional brick manufacturing based on plasticity, drying shrinkage, and firing behaviour. Waste marble powder was collected from marble processing industries located in the Hebbal industrial area of Bengaluru. The powder was sun-dried, sieved through a 75 μm sieve to remove coarse particles, and stored in airtight containers prior to use.

Chemical composition of the marble powder was determined by Energy Dispersive X-ray Analysis (EDX), revealing a composition rich in calcium oxide (CaO: 38.84%) and magnesium oxide (MgO: 35.04%) with moderate silica (SiO₂: 26.12%), consistent with a dolomitic calcite marble source. X-ray diffraction (XRD) analysis confirmed the dominance of calcite (CaCO₃) with characteristic peaks at approximately 29.4° 2 θ , accompanied by minor dolomite and trace quartz phases. Scanning electron

microscopy (SEM) of the raw powder displayed angular, fragmented particles with sharp edges and surface irregularities, indicative of mechanical processing residues.

2.2. Mix Proportions and Brick Preparation

Six mix compositions were prepared by partially replacing clay with WMP at levels of 0% (control), 5%, 10%, 15%, 20%, and 25% by dry weight. Dry materials were thoroughly blended in a mechanical mixer to ensure homogeneity. Potable water was added gradually to achieve a workable plastic consistency suitable for moulding. The mixtures were then hand-moulded or pressed into standard brick specimens (approximately 190 × 90 × 40 mm) following practices aligned with IS 1077:1992. Green bricks were dried under controlled shade conditions for 7–10 days to prevent cracking, followed by oven drying at 105 ± 5 °C to constant mass. Fired in a laboratory muffle furnace at 1000 °C (within the 900–1000 °C range indicated in IS 2117:1991), selected after preliminary trials at 900 °C, 950 °C, and 1000 °C" with a controlled heating rate and sufficient soaking period to achieve optimal vitrification and dimensional stability. Three replicate specimens were prepared and tested for each mix to ensure statistical reliability.

2.3. Testing Methods

Compressive strength was determined according to IS 3495 (Part 1):1992 using a universal testing machine. Water absorption and apparent porosity were evaluated by the boiling water method as per relevant ASTM and Indian standards. Initial rate of absorption (IRA) was measured following ASTM C67 procedures. Bulk density was calculated from dry mass and external volume. Efflorescence was assessed visually after partial immersion in distilled water as per IS 3495 (Part 3). Microstructural examination of fractured surfaces from the optimal mix was performed using SEM at magnifications of 1000× and 2000×. Environmental safety was verified through the Toxicity Characteristic Leaching Procedure (TCLP, USEPA Method 1311) on crushed samples of the 15% WMP bricks, with leachate analysed for heavy metals (As, Ba, Cd, Cr, Cu, Pb, Zn) via atomic absorption spectroscopy or ICP-MS and compared against USEPA regulatory limits.

3. Results and Discussion

3.1. Chemical Composition of Raw Materials

The chemical compositions of the base clay (from Tavarekere, Bengaluru) and waste marble powder (from local processing industries in Hebbal, Bengaluru) were determined using Energy-Dispersive X-ray Spectroscopy (EDS) and are summarised in Table 1. These compositions are critical for understanding firing behaviour, vitrification potential, and final brick properties.

Table 1. Chemical composition of clay and waste marble powder

Material	SiO ₂ (%)	Al ₂ O ₃ (%)	Fe ₂ O ₃ (%)	CaO (%)	MgO (%)
Clay	59.02	27.21	5.24	5.64	1.55
Marble Powder	26.12	—	—	38.84	35.04

The clay is silica- and alumina-rich (typical for brick-making clays), providing the structural skeleton and plasticity, with moderate fluxing oxides (Fe₂O₃, CaO) that aid vitrification at 1000 °C. The marble powder

is dominated by CaO and MgO from calcite and dolomite, acting as both filler and flux while contributing to pore formation at high replacement levels via CO₂ release during decarbonation. Minor oxides (Na₂O, K₂O, SO₃) in clay help optimise firing efficiency.

3.2. Compressive Strength

The compressive strength results for marble powder-incorporated bricks are presented in Table 2 and illustrated in Figure 1. Strength increased progressively with WMP content up to 15% replacement, reaching a maximum of 15.92 MPa for the CM15 mix—an improvement of 34.3% over the control brick (11.85 MPa). Beyond this optimum, strength declined, with CM25 recording 12.17 MPa. The enhancement at moderate replacement levels is primarily attributed to the microfiller action of fine calcite particles, which improve particle packing density, reduce inter-particle voids, and promote more efficient stress transfer within the matrix. Additionally, the fluxing oxides (CaO, MgO) derived from partial decarbonation during firing facilitate liquid-phase sintering and vitrification, leading to a denser, stronger ceramic bond (Munir et al., 2018; Sutcu et al., 2015). At higher dosages (>15–20%), excessive CO₂ evolution from CaCO₃ decomposition (occurring around 800–900 °C) generates additional porosity and potential microcracking if gas escape pathways are restricted, weakening the matrix and reducing inter-particle cohesion (Rasool et al., 2023). The observed trend aligns with literature indicating an optimal WMP range of 10–20% for strength maximisation in fired clay systems.

Table 2. Compressive strength of marble powder bricks at different replacement levels

% Marble Powder	Compressive Strength (MPa)	Change vs. Control (%)
Control (0%)	11.85	—
CM5 (5%)	12.98	+9.5
CM10 (10%)	14.23	+20.1
CM15 (15%)	15.92	+34.3
CM20 (20%)	14.33	+20.9
CM25 (25%)	12.17	+2.7

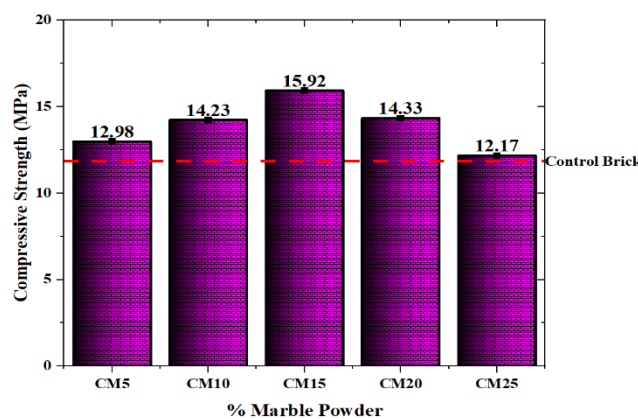


Figure 1: Compressive Strength of Bricks with Partial Marble Powder

3.3. Water Absorption, Porosity, and Initial Rate of Absorption

Water absorption, apparent porosity, and IRA exhibited parallel trends, decreasing to minimum values at 15% WMP before increasing at higher replacements (Table 3). Water absorption reduced from 14.21% (control) to 12.11% (CM15) as shown in Figure 2, porosity from 33.99% to 29.87% as shown in Figure 3, and IRA from 0.18 to 0.10 g/min/cm², as illustrated in Figure 4. These improvements stem from the combined microfiller and fluxing effects that refine pore structure, enhance matrix densification, and promote surface pore sealing during vitrification (Bilgin et al., 2012; Sufian et al., 2021). Reduced capillary connectivity limits rapid moisture ingress, which is beneficial for durability against freeze–thaw cycles, salt crystallisation, and efflorescence in masonry applications. At elevated WMP contents, decarbonation-induced porosity and reduced clay plasticity disrupt the continuous matrix, increasing open pore volume and permeability. The 10–15% range thus represents the practical optimum for impermeability and long-term durability.

Table 3. Water absorption and apparent porosity of marble powder bricks

% Marble Powder	Water Absorption (%)	Porosity (%)	IRA (g/min/cm ²)
Control (0%)	14.21	33.99	0.18
CM5 (5%)	13.97	32.95	0.15
CM10 (10%)	13.05	31.24	0.13
CM15 (15%)	12.11	29.87	0.10
CM20 (20%)	13.78	33.05	0.15
CM25 (25%)	15.43	36.10	0.18

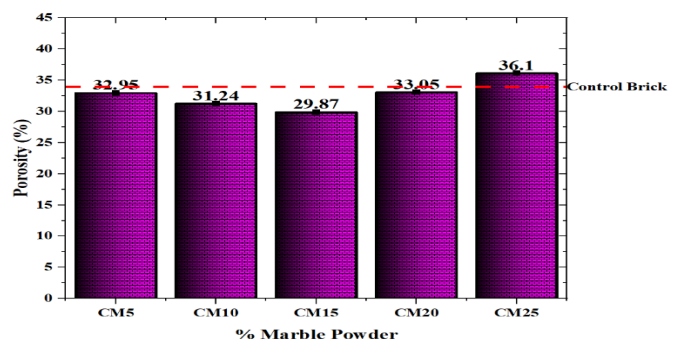
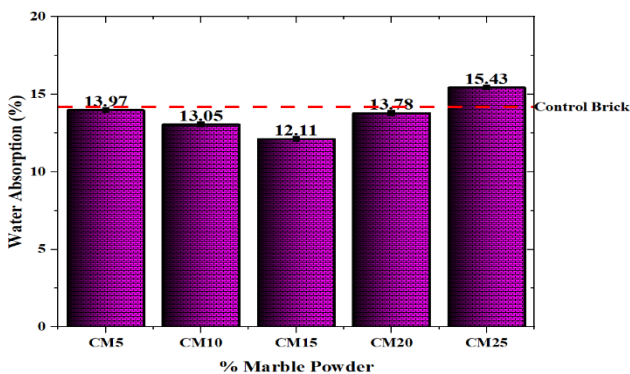


Figure 2: Water Absorption of Bricks with Partial Marble Powder

Figure 3: Porosity of Bricks with Marble Powder

3.4. Bulk Density and Efflorescence

Bulk density increased from 1.94 g/cc (control) to a maximum of 2.05 g/cc at 15% WMP (Table 4) as illustrated in Figure 5, attributable to the higher specific gravity of marble minerals (~2.6–2.8 g/cm³) relative to clay and the improved packing efficiency of the filler particles. This densification supports the observed strength gains and reduced permeability.

Table 4. Bulk density and efflorescence performance

% Marble Powder	Bulk Density (g/cc)	Efflorescence
Control (0%)	1.94	Nil
CM5 (5%)	1.95	Nil
CM10 (10%)	1.99	Nil
CM15 (15%)	2.05	Nil
CM20 (20%)	1.99	Slight
CM25 (25%)	1.95	Slight

Efflorescence testing revealed no visible salt deposits for control and CM5–CM15 specimens. Slight efflorescence appeared only at 20% and 25% replacements, likely due to excess soluble calcium compounds migrating to the surface. The absence of efflorescence up to the optimum level confirms good chemical compatibility and minimal risk of aesthetic or durability issues in service.

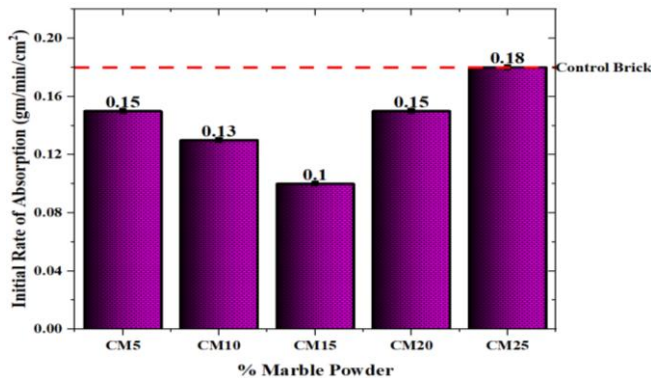


Figure 4: IRA of Bricks with Partial Marble Powder

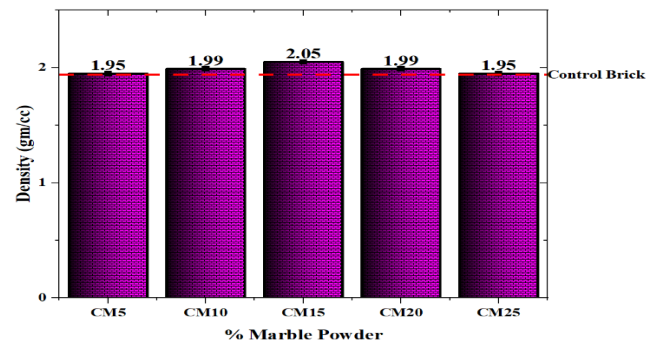


Figure 5: Density of Bricks with Partial Marble Powder

3.5. Microstructural Analysis and Environmental Safety

SEM micrographs of raw WMP revealed angular particles with rough surfaces and inter-particle voids, as illustrated in Figure 6. In contrast, the fractured surface of the CM15 brick exhibited a significantly denser microstructure in which marble particles were well embedded within the clay-derived matrix, surrounded by flaky clay platelets indicative of strong interfacial bonding as illustrated in Figure 7. The observed vitrification and reduced void space corroborate the macroscopic improvements in strength and impermeability. TCLP results for the CM15 bricks (Table 5) showed leachate concentrations of all monitored heavy metals (As, Ba, Cd, Cr, Cu, Pb, Zn) substantially below USEPA permissible limits. The immobilisation is facilitated by the incorporation of metals into the glassy/vitrified phases formed during firing and by the alkaline Ca-rich environment that promotes precipitation or sorption of potential contaminants (Kaouche et al., 2025). These findings confirm that bricks containing up to 15% WMP are environmentally safe for construction applications and do not pose risks of hazardous leaching under normal exposure conditions.

Table 5. TCLP leachate concentrations for CM15 bricks and regulatory limits

Contaminant	CM15 (mg/L)	Leachate	USEPA Limit (mg/L)	Status
Arsenic (As)	1.27		< 5	Compliant
Barium (Ba)	0.02		< 100	Compliant
Cadmium (Cd)	0.01		< 1	Compliant
Chromium (Cr)	0.51		< 5	Compliant
Copper (Cu)	0.023		< 100	Compliant
Lead (Pb)	0.90		< 5	Compliant
Zinc (Zn)	0.84		< 500	Compliant

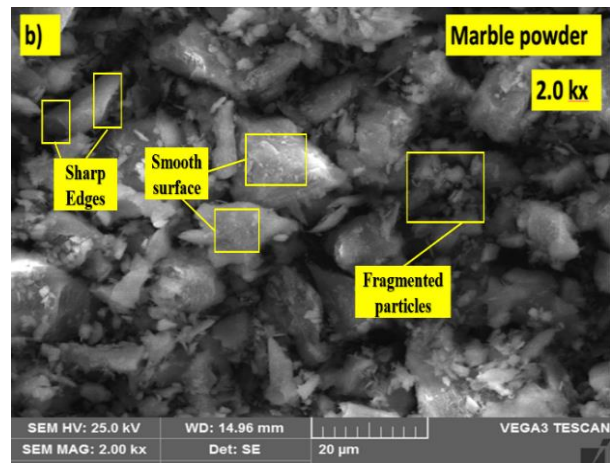
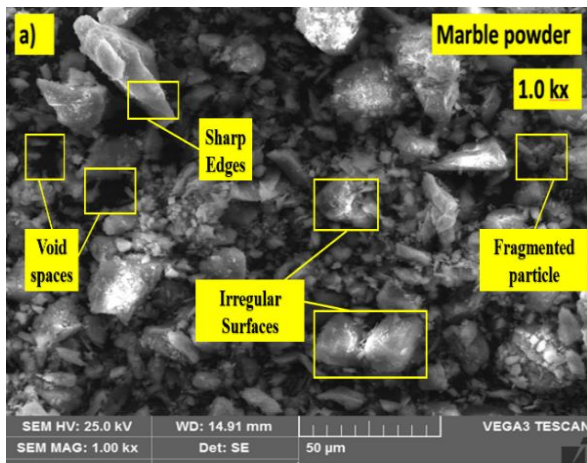


Figure 6: SEM Images of Marble Powder, a) 1000x, b)2000x

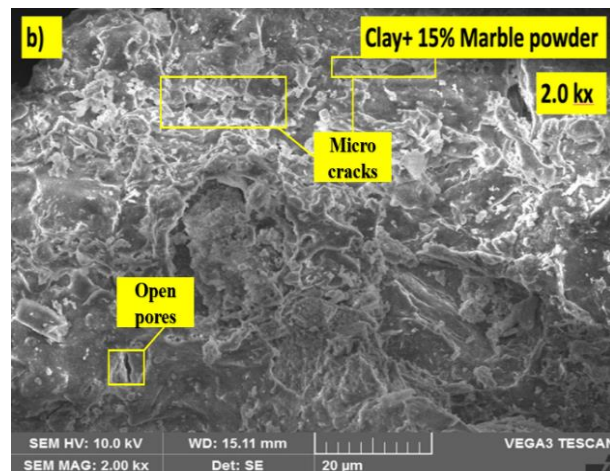
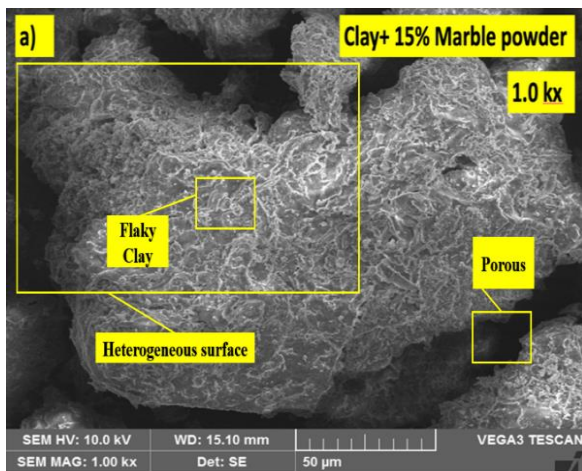


Figure 7: SEM Images of Clay + 15 % Marble Powder, a) 1000x , b)2000x

4. Conclusions

This investigation demonstrates that waste marble powder can be effectively utilized as a partial replacement for natural clay in fired brick production, delivering both performance enhancements and environmental benefits. The optimum replacement level of 15% by weight yielded a 34.3% increase in compressive strength (15.92 MPa), reductions in water absorption (to 12.11%), porosity (to 29.87%), and IRA (to 0.10 g/min/cm²), and a modest density increase to 2.05 g/cc. These improvements arise from the synergistic microfiller and fluxing actions of the calcite-dominated WMP, promoting matrix densification and vitrification. Higher replacement levels induce excessive porosity from carbonate decomposition, degrading properties. TCLP results confirmed full regulatory compliance for heavy metal leachability, establishing the environmental safety of the optimal formulation. The findings support the adoption of up to 15% WMP in structural clay bricks as a viable strategy for marble waste valorization, clay resource conservation, and advancement of sustainable construction practices in India. Future work should explore thermal insulation characteristics, pilot-scale production economics, and long-term in-service durability under Indian climatic conditions.

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