Investigating the Economic and Environmental Feasibility of White Marble Powder as a Partial Cement Replacement in Concrete

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Abstract

There is a growing push in the construction industry to adopt more sustainable materials due to the high carbon footprint of ordinary Portland cement. This study evaluates the use of white marble powder (WMP), a waste byproduct of marble processing, as a partial cement replacement in concrete. Concrete mixes were prepared with 0%, 10%, 20%, 30%, and 40% WMP replacing cement by weight, and tested for workability and mechanical properties (compressive, split tensile, and flexural strength). The 10% WMP mix exhibited the best overall performance, with 28-day compressive, tensile, and flexural strengths increased by approximately 13–14%, 12%, and 9–10% respectively compared to the control mix (0% WMP). Workability (slump) also improved with increasing WMP up to 40%, although mixes with ≥30% WMP showed noticeable strength reduction and potential workability issues (segregation) at the highest replacement. An economic analysis showed that replacing 10% of cement with WMP can reduce cement usage and cost by about 10% per cubic meter of concrete, and an environmental assessment indicated a roughly 10% reduction in CO_2 emissions associated with cement production at this replacement level. Higher replacement levels yield greater cost and CO_2 savings (up to 40% at 40% WMP) but with compromised strength. These findings, supported by recent literature, suggest that a moderate incorporation of marble powder (around 10–15%) is technically, economically, and environmentally feasible, achieving a balance between improved concrete workability, adequate strength, cost savings, and reduced carbon footprint.

Keywords: Sustainable construction, White marble powder, Cement replacement

1. Introduction

The construction industry is one of the largest consumers of materials globally, with concrete playing a pivotal role in infrastructure development. However, the production of cement, a key component of concrete, is energy-intensive and a significant contributor to global carbon dioxide (CO_2) emissions [1]. As the demand for sustainable construction materials grows, researchers are increasingly exploring alternative solutions to reduce the environmental impact of cement production.

In countries like Pakistan, which are rich in marble reserves, the marble processing industry generates substantial waste in the form of powder and slurry. This waste is often disposed of in landfills, leading to environmental issues such as land degradation and air pollution [2]. The reuse of marble waste presents an opportunity to mitigate these environmental challenges while promoting sustainable construction practices.

 https://doi.org/10.64615/fjes.1.Special Issue.2025.57

White marble powder (WMP), a byproduct of marble cutting and processing, has shown potential as a partial replacement for cement in concrete. Rich in calcium carbonate ($CaCO_3$), WMP possesses chemical properties that make it suitable for use in concrete mixtures [3]. By replacing cement with WMP, not only can cement consumption be reduced, but marble waste can also be repurposed, addressing both environmental and economic concerns.

Use While previous studies have explored the use of marble powder as a cement replacement, this research uniquely focuses on the economic and environmental feasibility of WMP in the context of Pakistan, where marble waste is abundant but underutilized. This study evaluates the mechanical properties of concrete with varying WMP replacement levels (0%, 10%, 20%, 30%, and 40%), including workability, compressive strength, tensile strength, and flexural strength. Additionally, it provides a comprehensive analysis of the cost savings and CO_2 emission reductions associated with WMP use, offering actionable insights for sustainable construction practices.

This investigation contributes to the ongoing research on alternative cementitious materials by determining the optimal replacement level of WMP for structural applications. It also highlights the dual benefits of WMP: reducing the environmental impact of marble waste disposal and lowering the carbon footprint of cement production. By integrating WMP into concrete production, this study aims to advance sustainable construction practices in Pakistan and beyond.

2. Materials and Methods

The White marble powder possibility to be used as a partial substitute of cement in the concrete production is studied in this study. The methodology involved material selection, test specimen concrete mix design, casting and curing, and performance of workability and compressive, flexure and tensile strength test.

2.1. Material

2.1.1. Cement

DG 53 grade Ordinary Portland Cement (OPC), conforming to ASTM C150 standards, was used as the primary binder in all concrete mixtures. Its consistency, setting time, and strength characteristics ensured compatibility with marble powder replacements.

2.1.2. Marble Powder

White marble powder, a byproduct of marble processing, was sourced locally. The chemical composition of the marble powder, determined through analysis, is presented below in table 1.

Table 1 The chemical composition of the white marble powder

Component	Percentage
Ca_2	84.4
SiO_2	2.31
SiO_3	2.02
MgO	4.05
Al_2O_3	3.5
Fe_3O_2	0.068
Na_2O	0.039
K_2O	0.018
Mn_2O_3	0.011
Other element	Trace amount

2.1.3. Fine Aggregate

Natural river sand was used as fine aggregate. It met the grading and particle size requirements specified in ASTM C33 standards, ensuring appropriate workability and strength in concrete mixes.

2.1.4. Coarse Aggregate

Crushed stone with a nominal size range of 10 mm to 20 mm was used as coarse aggregate. It was clean, angular, and free of deleterious materials, ensuring proper interlocking in the concrete matrix.

2.2. Mix Design

The concrete mix for this study was formulated to evaluate the impact of substituting cement with white marble powder on concrete performance. Designed for M20 grade, the mix ensured an optimal balance of strength and workability. A consistent mix ratio was maintained across different replacement levels, with varying percentages of marble powder as detailed in Table 2. The total cementitious material (cement + marble powder) was kept constant, ensuring comparable results across all mixes. The total binder content (cement + WMP) was kept constant at 300 kg per cubic meter of concrete in all mixes, so, the 10% WMP mix contained 270 kg cement + 30 kg WMP per m^3, the 20% mix had 240 kg cement + 60 kg WMP, and so on. Table 1 summarizes the mix proportions for each case:

Table 2 M20 grade mix proportion

Cement (%)	Marble Powder (%)	W/C Ratio	Mix Ratio
100	0	0.46	1:1.5:3
90	10	0.46	1:1.5:3
80	20	0.46	1:1.5:3
70	30	0.46	1:1.5:3
60	40	0.46	1:1.5:3

All materials were accurately weighed based on the specified mix proportions to ensure consistency. A mechanical mixer was used to blend the materials uniformly. Initially, fine and coarse aggregates were dry mixed with cement and marble powder. Water was then gradually added during mixing until a uniform concrete mix was achieved.

The concrete was poured into cylindrical molds (100 mm × 200 mm) in three layers, with each layer compacted using a tamping rod to remove air voids and ensure consistent density. After 24 hours, the specimens were demolded and submerged in water tanks for curing. Curing periods of 7, 28, and 56 days were established to assess both short-term and long-term concrete performance.

The w/c ratio of 0.46 was chosen to balance workability and strength. The range of 0–40% replacement was selected to evaluate the feasibility and limitations of marble powder as a cement substitute. Cylindrical specimens were chosen for their standard use in compressive strength testing, ensuring reliable comparison across mixes.

2.3. Testing Methods and Calculations

The experimental phase of this research focused on assessing the performance of concrete mixtures incorporating different proportions of marble powder as a replacement material. The evaluation involved conducting slump tests to measure workability and compressive, tensile, and flexural strength tests to determine mechanical properties. The following sections provide a comprehensive overview of each testing method, including the calculations applied.

2.3.1. Slump Test

The slump test evaluates the workability of concrete, verifying it achieves the desired consistency for construction purposes. It was conducted following ASTM C143 standards. A 300 mm tall slump cone was filled with fresh concrete in three layers, each tamped 25 times with a tamping rod to remove air voids. After carefully lifting the cone, the concrete settled under its own weight. The slump value, measured in millimeters (mm), was determined as the height difference between the cone and the subsided concrete.

2.3.2. Compressive Strength Test

Compressive strength, a key indicator of concrete's load-bearing capacity, was evaluated following ASTM C39 standards. Cylindrical specimens (100 mm × 200 mm) were tested after 7, 28, and 56 days of curing. Each specimen was placed in a universal testing machine (UTM), and a load was applied at a constant rate until failure occurred. The maximum load recorded was used to compute the compressive strength.

2.3.3. Tensile Strength Test

The tensile strength test assesses concrete's capacity to withstand tension, essential for preventing cracks. Cylindrical specimens (100 mm × 200 mm) underwent split tensile strength testing in accordance with ASTM C496 standards. A load was applied along the vertical diameter of each specimen until it failed. The split tensile strength, f_t, was determined using the provided formula. $f_t = \frac{2P}{\pi DL}$ where *P* is the failure load, *D* is cylinder diameter (100 mm), and *L* is length (200 mm). The average of three specimens was taken for each mix

2.3.4. Flexural Strength Test

Flexural strength indicates concrete's capacity to withstand bending or cracking under applied loads. Beam specimens (100 mm × 100 mm × 500 mm) were evaluated using a three-point bending configuration, following ASTM C78 standards. The flexural strength, f_{fr}, was determined using the provided formula. $f_{fr} = \frac{PL}{bd^2}$ for a beam that fails in the middle third, where *P* is the max load, *L* the span (300 mm), *b* the width (100 mm), and *d* the depth (100 mm).

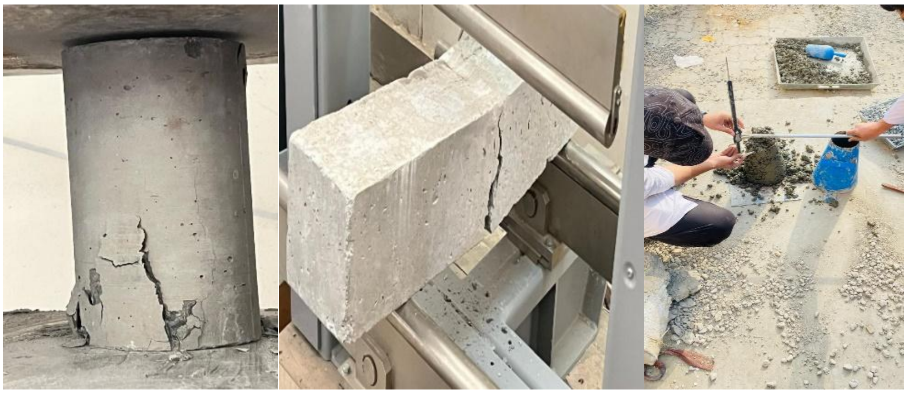

Fig. 1 Testing of concrete

2.3.5. Economic and Environmental Analysis

To assess the economic and environmental advantages of substituting cement with white marble powder in concrete, the cost of Ordinary Portland Cement (OPC) was set at 1400 PKR per 50 kg bag, or 28 PKR/kg. The control mix (0% replacement) required 300 kg of cement per cubic meter. Cement replacement levels of 10%, 20%, 30%, and 40% were evaluated for cost savings, with marble powder assumed to be a waste product available at minimal cost. Savings were calculated by comparing the cement cost in the control mix to that in mixes with partial replacement.

$$\text{Cost per kg} = \frac{\text{Cost per bag}}{\text{Weight per bag}} = \frac{1400}{50} = \frac{28\text{PKR}}{\text{kg}}$$

Cement production emits approximately 0.9 kg of CO_2 per kg of cement. By reducing the amount of cement used in the mix, CO_2 emissions were proportionally reduced. Results and Discussion

3. Results

The experimental findings on workability, compressive strength, tensile strength, and flexural strength of concrete incorporating different percentages of white marble powder as a cement replacement are evaluated below.

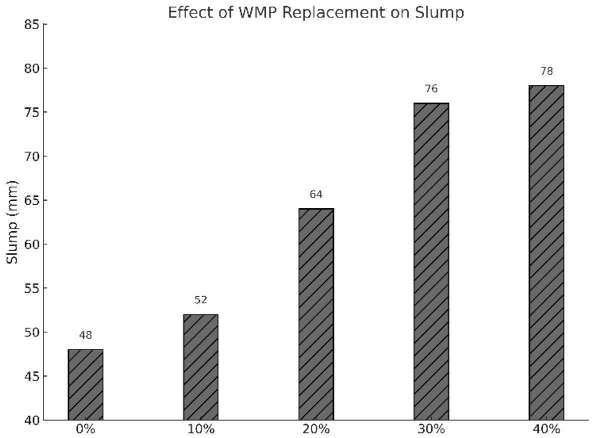

Fig. 2. Slump test results

The slump values indicate a consistent increase in workability as the percentage of marble powder increases. Marble powder is finer than cement and reduces internal friction in the mix, leading to better flowability [4]. Figure 2 shows that workability increases with higher WMP replacement levels, peaking at 40%. However, beyond 30%, the high slump may lead to segregation and bleeding, making 10–20% replacement levels more practical for field applications. Enhanced workability reduces the need for additional water or chemical admixtures, lowering costs and improving ease of placement [5].

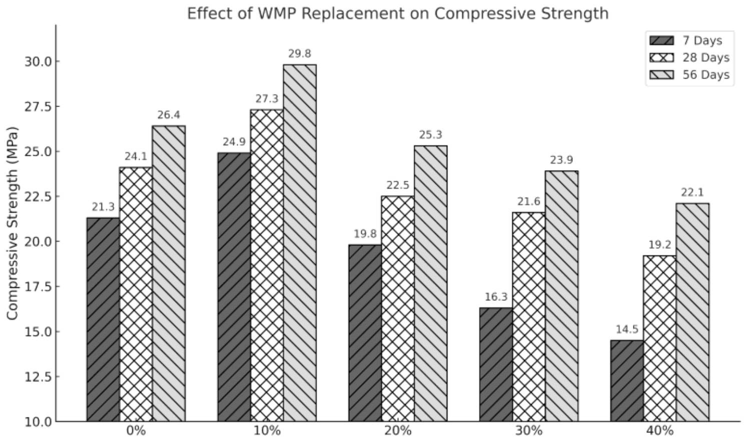

Fig. 3. Compressive strength results

Figure 3 indicates that compressive strength improves at 10% WMP replacement, with a 13.8% increase at 28 days. However, strength declines at higher replacement levels, suggesting that 10% is the optimal balance between performance and cement reduction. This increase is attributed to the filler effect and pozzolanic activity of marble powder, which improves particle packing and promotes secondary hydration [6]. The strength decreased but remained comparable to the control mix. At 28 days, the compressive strength was 6.25% lower than the control, a balance between filler benefits and cement dilution. Strength reduced substantially due to excessive cement replacement, which compromised the binding properties of the mix [7].

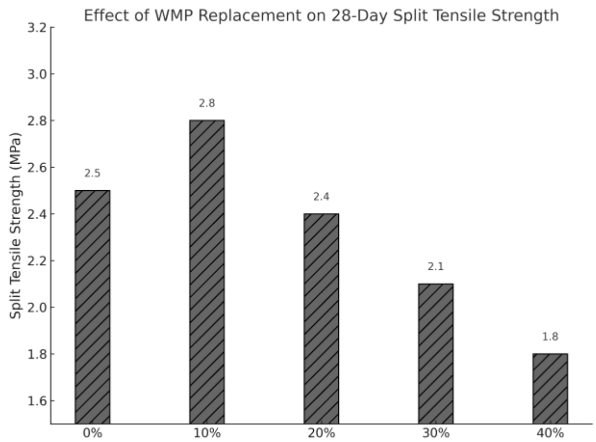

Fig. 4. Tensile Strength results

The tensile strength of 2.5 MPa at 28 days is consistent with typical M20 concrete. Tensile strength increased by 12% compared to the control, likely due to improved particle distribution and bonding within the matrix. Tensile strength decreased progressively with higher replacement levels, mirroring the trends observed in compressive strength. Marble powder improves tensile performance at moderate replacement levels but diminishes tensile capacity at higher levels [8].

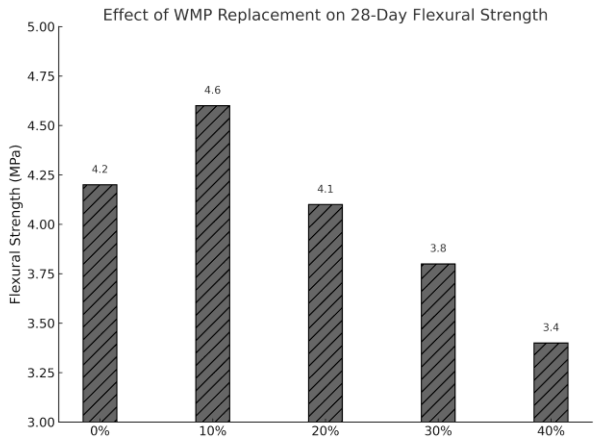

Fig. 5. Flexure Strength results

The flexural strength of 4.2 MPa aligns with expected performance for M20 concrete. Flexural strength increased by 9.5%, suggesting enhanced microstructural integrity at moderate replacement levels. Strength decreased progressively due to reduced cement content, which weakens the bonding between aggregates. The use of 10% marble powder enhances flexural performance, making it suitable for structural applications requiring improved bending resistance.

Table 3 Fresh and harden performance of WMP Concrete

WMP Replacement (%)	Slump (mm)	Compressive Strength (MPa) - 7 days	Compressive Strength (MPa) - 28 days	Compressive Strength (MPa) - 56 days	Split Tensile Strength (MPa) - 28 days	Flexural Strength (MPa) - 28 days
0	48	21.3	24.1	26.4	2.5	4.2
10	52	24.9	27.3	29.8	2.8	4.6
20	64	19.8	22.5	25.3	2.4	4.1
30	76	16.3	21.6	23.9	2.1	3.8
40	78	14.5	19.2	22.1	1.8	3.4

While improvements in mechanical strength were observed with lower WMP replacement levels, it is essential to explore the durability of concrete at higher replacement levels. Although the increase in mechanical strength at 10% WMP replacement was significant, a decline in strength was noticed at higher levels. This reduction in strength may be linked to the changes in the microstructure, leading to potential durability concerns at higher replacement levels. The effect of these changes on freeze-thaw resistance, water absorption, and chemical durability needs further exploration to evaluate the long-term performance of concrete with high WMP content.

3.1. Cost Analysis

The cost analysis showed significant savings with increasing levels of cement replacement. The details are summarized below in table 4.

Table 4 Cost analysis

Replacement Level (%)	Cement Used (kg)	Cement Cost (PKR)	Cost Savings (PKR)
0 (Control)	300	8,400	0
10	270	7,560	840
20	240	6,720	1,680
30	210	5,880	2,520
40	180	5,040	3,360

At the optimal replacement level of 10%, the cost savings per cubic meter of concrete are 840 PKR, representing a 10% reduction in cement costs. Higher replacement levels yield progressively greater savings, with a maximum saving of 3,360 PKR/m³ at 40% replacement. However, these higher levels compromise the strength properties of concrete. The economic feasibility of marble powder replacement is particularly attractive for large-scale projects in Pakistan, where cost reductions can translate into substantial savings.

3.2. Environmental Impact

Replacing cement with marble powder directly reduces CO_2 emissions associated with cement production. The emissions avoided for different replacement levels are calculated as follows in table 5.

Table 5 CO_2 emissions

Replacement Level (%)	Cement Reduction (kg)	CO_2 Emission Reduction (kg/m³)
0 (Control)	0	0
10	30	30×0.9 =27
20	60	60×0.9 =54
30	90	90×0.9 =81
40	120	120×0.9 =108

At the optimal 10% replacement level, the CO_2 emission reduction is 27 kg per cubic meter of concrete. Replacing 40% of cement results in a reduction of 108 kg of CO_2 per cubic meter, though this level is not feasible due to compromised strength. Adoption of marble powder in concrete production can significantly reduce the carbon footprint of construction projects in Pakistan, aligning with global sustainability goals.

4. Conclusion

Based on the findings of this study, it is recommended to use 10% White Marble Powder (WMP) as an optimal cement replacement in structural concrete, as it offers a balance between improved workability and mechanical performance without compromising strength. For non-structural applications such as pavements or curbs, higher WMP levels (20%-30%) can be considered, providing cost savings and workability improvements. However, for durability-critical projects, particularly in aggressive environments, WMP replacement should be limited to 10%-20% to avoid issues related to increased porosity and water absorption. Large-scale projects, such as highways or bridges, can benefit from cost savings by using WMP, as the waste material is locally available and inexpensive. It is also recommended to conduct pilot projects and further studies on long-term performance, including the durability of WMP-based concrete, to better understand its feasibility in diverse environmental conditions. Encouraging the adoption of WMP in construction practices can significantly contribute to more sustainable and cost-effective concrete production.

Acknowledgments. We gratefully acknowledge the Department of Civil Engineering, The Islamia University of Bahawalpur, for their support and facilities. Our thanks also go to the marble industry professionals who provided the marble powder used in this study, aiding the advancement of sustainable construction practices.

Abbreviations

The following abbreviations are used in this manuscript:

WMP	White Marble Powder
OPC	Ordinary Portland Cement
CO_2	Carbon Dioxide
ASTM	American Society for Testing and Materials
w/c	Water-to-Cement Ratio
UTM	Universal Testing Machine
$CaCO_3$	Calcium Carbonate
CaO	Calcium Oxide
SiO_2	Silicon Dioxide
Al_2O_3	Aluminum Oxide
MgO	Magnesium Oxide
Fe_2O_3	Ferric Oxide (Iron Oxide)
Na_2O	Sodium Oxide
K_2O	Potassium Oxide
Mn_2O_3	Manganese Oxide
LCA	Life Cycle Assessment
PKR	Pakistani Rupee

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