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Review

Marble Powder as a Sustainable Cement Replacement: A Review of Mechanical Properties

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Abstract: The sudden increase in industrialization has reduced the availability of natural building materials and triggered the growing awareness of sustainable practices within the construction industry. The study presented here deals with marble powder, which is one of the by-products obtained from the marble industry, as a cement replacement in concrete mixtures. The main aims will be to investigate the impact of marble powder waste materials on the mechanical properties of concrete and to promote the recycling of various industrial wastes for environmental sustainability. Material testing was conducted with the levels of substitution of marble powder for cement ranging from 0% to 50%, and the resulting concrete was evaluated for compressive and tensile strength over different curing periods. The results show that concrete compressive strength and tensile strength are most efficiently improved when marble powder replacement is up to 10–15%, attaining its full potential after 28 days. Beyond this replacement level of 15%, the mechanical properties decrease, suggesting that higher substitution levels may not be effective. This paper consolidates findings, provides a novel comparative analysis, and addresses key challenges regarding the use of marble powder, providing room for the future industrial development of supplementary cementitious materials (SCMs), eventually leading to sustainability in the construction sector.

Keywords: concrete durability; waste materials; cement admixture; marble powder; supplementary cementitious materials (SCMs)

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1. Introduction

Rapid industrialization and infrastructure development over the last few decades have tremendously reduced the availability of natural building materials. Over the last decade, green and sustainable building materials have witnessed a significant increase in attraction worldwide. The requirement for sustainability has gained further significance, not only for present times but also for future growth of the construction industry, through awareness being spread among participants about environmental concerns, apart from its extensive utilization in construction.

Moreover, this development generates significant waste from industries, adversely affecting the environment's CO_2 emissions. One effective solution to these problems is to seek methodologies that minimize the excessive use of natural materials. One such method is the rational use of industrial waste in concrete mixes. Several industrial by-products can serve as additives in concrete, with some of their properties coinciding with the primary components of the mix [1–4].

Marble, a material that has been used since ancient times in construction, is processed in many parts of the world, generating substantial amounts of waste and by-products. The mechanical properties of concrete, when combined with marble powder and limestone waste, have shown improvements, offering greater sustainability for the industry. One of the major problems is the disposal of waste from the marble industry, which poses environmental challenges. For example, in Romania, approximately 100 tons of marble powder slime waste is generated daily, leading to environmental pollution and potential health risks [5].

In addition to its environmental impacts, this waste can also be repurposed. Marble powder can be used not just as an admixture but also in the production of other building materials, such as ceramic bricks [6,7]. Figure 1 illustrates the percentage of waste generated by industrial marble processing, most of which is being dumped as rejected material. Net marble gain refers to workable marble after processing, whereas quarrying, processing, and polishing wastes refer to wastes left from these processes, which include irregularly shaped pieces and fine marble dust or slurry. Often, 30% of the marble being processed ends up as slurry waste; when dried, it contributes to dust pollution and displaces agricultural land, rendering the land infertile. Additionally, the waste has caused detrimental conditions for surrounding areas, contaminating surface and underground water reserves [7,8].

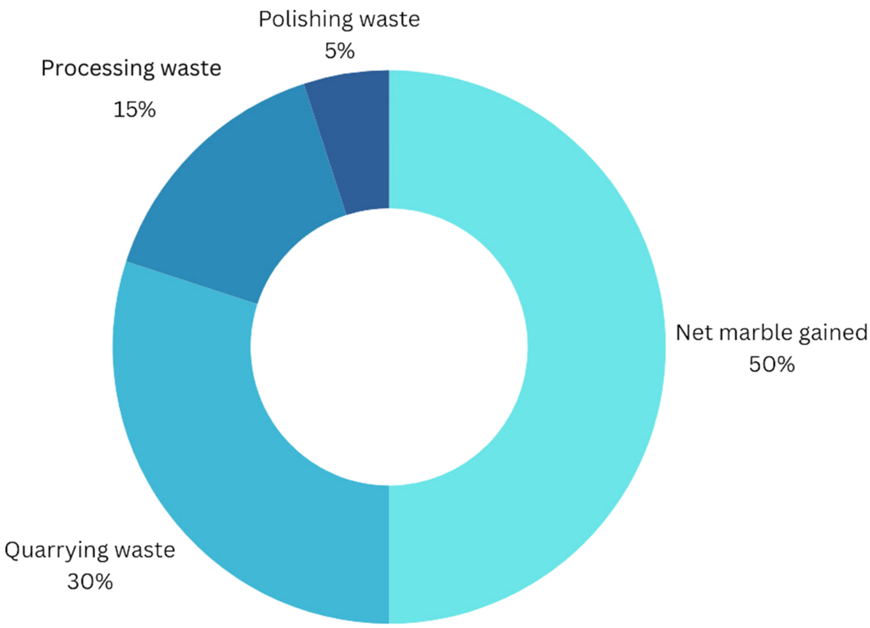

Figure 1. Percentage of waste generated by industrial marble processing [8].

Cement industries produce around 5% of the total man-made CO_2 emissions [9]. Interestingly, concrete life cycle assessment (LCA) revealed the astonishing results that energy consumption during the manufacturing of concrete is relatively high, i.e., 0.25 GJ/ton, as compared to the mere extraction of raw materials, requiring only 0.13 GJ/ton. This can be explained by the fact that raw materials such as gravel, sand, and water are readily available. The production of cement, however, consumes much more energy, i.e., about 70%, or 1.18 GJ/ton. Replacing the waste marble powder at a rate of just 15% of the cement will reduce energy consumption by approximately 1.05% [9,10].

Compressive strength, in most cases, is considered to be the most significant mechanical characteristic of cementitious construction materials. It is one of the most critical parameters involved in the design of concrete structures. It is a measure of performance in structural engineering, and it plays an imperative role in concrete structure design [11–13]. Several methods exist to determine the strength of concrete, and these methods are applicable in the fracture mechanics of concrete, helping to estimate its strength. Concrete materials are well-known for their high compressive strength but relatively low tensile strength. In structural design, tensile loads are typically avoided in concrete structures due to this limitation. However, tensile strength remains one of the key properties of concrete and is essential for the safety of a structure [14,15].

This paper reviews marble powder as a cement replacement material, considering its effect on the strength and sustainability of concrete, while exploring a wider range of replacement levels, establishing that the 10–15% replacement level is most suitable for enhancing the mechanical properties of concrete. It also discusses the reutilization of marble waste, which equals "between 690,000 and 920,000 tons generated annually" [16], reducing CO_2 emissions and hence, assisting in achieving sustainable development in the construction arena. The review provides new insights into the mechanical performance and long-term durability of marble powder concrete, thereby offering a more environmentally friendly alternative for the industry.

Overall, this review provides a comprehensive, advanced, and up-to-date synthesis of developments in the use of marble powder as a sustainable cement replacement in concrete, specifically emphasizing its effects on compressive and tensile strength, workability, and environmental sustainability. In addition to summarizing the state-of-the-art findings, this review identifies key challenges in the field and offers possible solutions, while also projecting future research trends and directions. By consolidating all relevant data and insights into one document, this review serves as a valuable resource for researchers, engineers, and policymakers aiming to advance sustainable construction practices.

The following are the primary contributions of this review paper:

- Comprehensive Overview: this review consolidates the research and state-of-the-art findings on the durability and mechanical characteristics of concrete made with marble powder, including a broad spectrum of replacement levels (0–50%) and identifying optimal substitution levels (10–15%).
- Focus on Environmental Impact: the paper emphasizes the role of marble powder in reducing carbon emissions and conserving natural resources, making a vital contribution to green construction practices.
- Comparative Analysis: a novel aspect of this review is the comparative analysis of results from multiple studies, providing clarity regarding compressive and tensile strength trends, workability changes, and durability characteristics at different replacement levels.
- Addressing Challenges: this review identifies and discusses key challenges, including the performance of marble powder concrete under extreme environmental conditions (e.g., freeze–thaw cycles, sulfate-rich environments) and the variability of waste marble powder properties.
- Future Directions: the review projects future trends in research, such as the integration of marble powder with other supplementary materials (e.g., fly ash, nano-silica) and mix design optimization to strike a balance between sustainability, strength, and workability.

1.1. Concrete Behavior and Sustainability

Siliceous limestone, aluminosilicate, or calcium aluminosilicate substances are supplementary cementitious materials (SCMs), soluble or not, that replace a portion of clinker in the manufacture of cement or a portion of cement in concrete mix. Many of the SCMs used today are byproducts of different industries, e.g., fly ash is obtained from the electrical generation industry. Some SCMs are naturally occurring minerals, whose processing costs are much lower than those of Portland cement. As a rough example, Portland cement clinker is approximately 3.5 GJ/t clinker in terms of thermal energy intensity [17].

SCMs can be made from a variety of materials, including biomass ashes, industrial byproducts, and raw and calcined natural minerals. Partially substituting SCMs for Portland clinker is one of the most popular and efficient strategies to lower cement production costs and CO_2 emissions. Currently, an estimated 800 million tons of materials like fly ash and blast furnace slag are utilized annually as SCMs. However, between 5 and 8% of the world's CO_2 emissions (see Figure 2) still come from the cement industry. Instruments for evaluating the effects, energy usage, and CO_2 emissions of construction products should meet international standards [18–22]. If no further action is taken, this share could rise beyond 25% by 2050 [23]. The cement of the future, whether Portland or another type, will be blended with residues from other industries. Currently, blended Portland cement containing one or more SCMs already constitutes the majority of cementitious binders produced. New SCMs will need to emerge as the demand for sustainable materials grows with the development, application, and management of concrete life cycle analysis (LCA) [24–28]. LCA methodology might be cumbersome to a non-expert; thus, there has been a shift towards the use of simplistic tools such as the ecological footprint and carbon footprint. These latter two are all emission accounting tools and thus, are easy to apply [29]. The increasing societal pressure for sustainable waste management and resource efficiency in a more circular economy will continue to drive the expansion and diversification of SCMs, both in combination with Portland cement and in other emerging cementitious materials. Since most SCMs are by-products of other processes, their quality has traditionally been secondary to the efficiency of the primary industrial activity. This has often resulted in suboptimal SCM quality and significant variability between sources over time [30,31], sometimes preventing the use of environmentally friendly materials due to their practical, technical, and economic impacts [32,33].

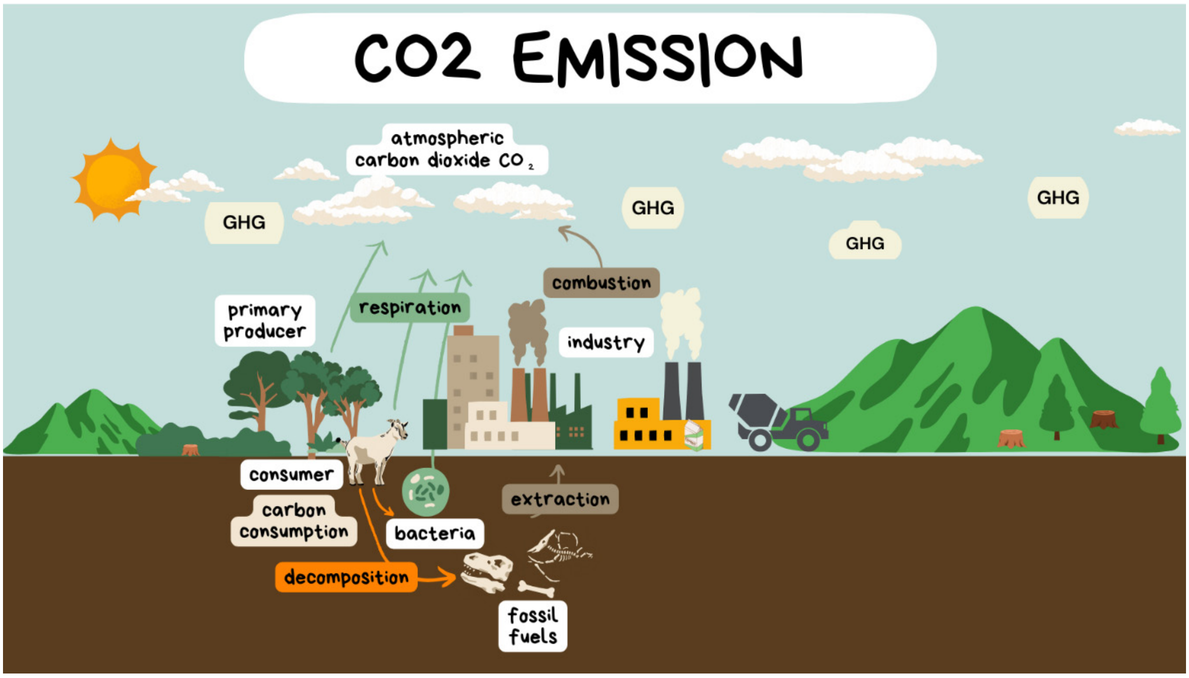

Figure 2. Carbon cycle: CO_2 emissions and their sources.

SCMs can be classified as industrial waste materials [34]. Sustainability regarding the built environment is based on important principles of resource conservation, life cycle cost, and human-friendly design. Resource conservation utilizes the concept of the 3Rs (reduce, reuse, and recycle), which are widely employed in the construction and manufacturing industries [35]. The general chemistry of SCMs, except for fine limestone, which is not discussed further here, is characterized by a lower calcium content compared to that of Portland cement [36].

1.2. Mechanical Testing of Concrete

The compressive strength test is by far the most common test carried out on concrete. This mainly stems from the fact that the test is easy and relatively inexpensive to carry out [37,38]. Depending on various testing standards, compressive concrete strength is determined using different specimen geometries. Among others, the most used specimen geometries are cylinders, possessing a slenderness ratio of two, and cubes. Most of the studies investigate the effect of shape on compression strength, and some relationships have been proposed, in most cases, using a technological approach. This idea often overshadows the fact that the failure of the specimen is directly correlated with the initiation and spread of fracturing processes. Experimental findings consistently demonstrate that a localized microcracked area forms during periods of high stress, which leads to specimen failure [37,39,40].

Brittle fracture theory states that the largest crack perpendicular to the applied load is what causes a specimen to fail. Since the occurrence of such a crack is a stochastic problem, the specimen's strength is influenced by its size and shape. Larger specimens are more likely to contain critical cracks, increasing the probability of failure initiation [41]. In the case of concrete, the energy released during the initiation of cracking may be insufficient to sustain crack propagation; it can be obstructed by a large pore or a more malleable material, which requires greater energy to break [42].

Flexural strength is crucial for assessing concrete durability and performance under load. Ref. [43] highlights that incorporating marble dust (MD) as a cement replacement enhances flexural strength by 7.8% at an optimal 6% replacement level due to its filling effect. Granite dust (GD) performs even better, with a 10.7% improvement at the same replacement level, attributed to its pozzolanic activity. Nano alumina (NA) significantly enhances flexural strength, achieving an 11.7% increase at a 1% addition by refining pores and accelerating hydration. Combining additives, such as 6% GD + 1% NA, results in the highest improvement of 13.6%, demonstrating synergistic effects. The potential of marble powder and supplementary materials to enhance concrete's mechanical properties while promoting sustainable construction practices is high.

Tensile strength is one of the most important material parameters in concrete structure analysis. Often, it is determined from either a direct pull test or a splitting tensile test. Although the concept of both tests is extremely simple, they proved to be quite complicated to perform in a manner that would yield trustworthy findings, regardless of specimen size and boundary circumstances. Traditionally, cylindrical specimens of 300 mm in length and 150 mm in diameter are used to perform the splitting tensile test, also known as the Brazilian test. The utilized dimensions are appropriate for the preparation of representative test samples of almost all the fiber-reinforced concrete mixtures. However, this splitting tensile test, as with the direct tension tests, also has several disadvantages. Another disadvantage of the direct tension tests is that they do not provide suitable data concerning post-crack behavior. The tensile strength in the splitting tensile test measures only tensile strength; in the case of normal-strength concrete, the tensile strength obtained via this test usually yields an actual uniaxial tensile strength of the material about 10–40% higher than the results of other tests [44].

1.3. Particle Size Influence on Mechanical Properties

The particle size distribution and shape of WMP significantly influence the mechanical properties and performance of concrete [45] in the following ways:

- Smaller particles enhance the packing density by filling voids, resulting in improved strength, durability, and reduced permeability.
- Angular particles provide better mechanical interlocking, enhancing structural integrity.
- Rounded particles improve the flowability and workability of the concrete mix.
- Optimal replacement ratios, typically, below 15% replacement, maintain compressive, tensile, and flexural strengths, while higher ratios increase porosity and reduce performance [45].
- Fine particles accelerate the hydration process due to their larger surface area, promoting the formation of dense, crystalline microstructures.
- Balanced particle size distributions improve density, reduce shrinkage, and enhance resistance to cracking.

2. Marble Powder

Marble is predominantly composed of calcium carbonate ($CaCO_3$); the marble characteristics shown in Table 1. The extraction and processing of marble for various applications generate substantial waste. Mining techniques, particularly blast mining, contribute significantly to this waste stream. Two primary types of waste are generated [46], as follows:

- Disintegrated rocks—large fragments and chunks of marble resulting from the blasting and excavation process.
- Fine-grained powder—produced during the various stages of marble processing, such as cutting, shaping, and polishing, resulting in a significant amount of fine marble dust.

Table 1. Marble characteristics.

Physical Appearance	
Color	White
Form	Powder
Odor	Odorless

2.1. Environmental Challenges of Marble Waste Disposal

The construction and manufacturing industries generate significant amounts of marble waste, primarily in the form of dust and small chips. This waste often ends up in landfills, contributing to environmental pollution and resource depletion [47]. The disposal of marble waste poses several environmental challenges:

- Landfill space: landfills are rapidly filling up, and the disposal of large volumes of marble waste exacerbates this problem.
- Water pollution: leachate from landfills containing marble waste can contaminate groundwater and surface water, harming aquatic ecosystems.
- Air pollution: dust from uncovered marble waste piles can be carried by wind, contributing to air pollution and respiratory problems.
- Resource depletion: marble is a finite natural resource, and its extraction and processing can have significant environmental impacts.

2.2. Sustainability Goals of the Construction Industry

The construction industry is increasingly focused on sustainability, aiming to minimize its environmental impact and conserve natural resources [48]. Key sustainability goals include the following:

- Reducing carbon emissions: cement manufacture, a key ingredient in concrete, uses a lot of energy and produces a lot of greenhouse gas emissions [49].

- Minimizing waste production: debris from building and demolition is among the enormous volumes of garbage produced by the construction sector. Reducing waste production is crucial for sustainability [50].
- Promoting resource efficiency: utilizing recycled and reclaimed materials, such as marble waste, may lessen the negative effects of building on the environment and aid in the conservation of natural resources [51].

2.3. Marble Powder as a Sustainable Cement Substitute

Researching the use of marble powder as a cement alternative is crucial given the environmental issues associated with disposing of marble waste and the building industry's sustainability objectives. In concrete, marble powder, a fine-grained substance produced by grinding marble, can partially substitute cement [52]. Marble composition is shown in Table 2. This strategy has several possible advantages:

- Waste reduction: using marble waste in construction applications can significantly reduce the amount of waste sent to landfills [53].
- Reduced carbon emissions: replacing cement with marble powder can lower the carbon footprint of concrete production [54].
- Improved material properties: in some cases, the addition of marble powder can enhance the strength and durability of concrete [55].

2.4. Cost-Efficiency and Eco-Efficiency of Marble Powder

The use of marble powder as a cement replacement offers potential economic and environmental benefits, aligning with sustainable construction practices [56].

2.4.1. Cost-Efficiency:

Reduced Material Costs:

- By partially replacing cement with marble powder, construction projects can potentially lower material costs [57].
- Marble powder can be significantly cheaper than Portland cement, especially when sourced locally from waste streams.

Waste Reduction and Disposal Costs:

- Utilizing marble waste as a construction material diverts it from landfills, reducing the associated disposal costs.
- Utilizing marble waste as a construction material can also lead to lower environmental impact fees and fines associated with waste disposal.

2.4.2. Eco-Efficiency

Reduced Carbon Footprint:

- Cement production is highly energy-intensive and a major source of greenhouse gas emissions [58].
- Reducing cement consumption by incorporating marble powder can significantly lower the carbon footprint of concrete production [7].

Resource Conservation

- Utilizing waste marble powder conserves natural resources by reducing the demand for virgin materials [59].

Waste Minimization

- By effectively utilizing waste materials, A more circular economy can be adopted by the construction sector, minimizing waste generation and promoting resource recovery.

Table 2. Marble chemical composition.

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	SO_3	LOI	[Ref.]
28.35	0.42	9.7	-	16.25	-	-	-	[60]
0.67	0.49	0.2	53.79	0.71	-	0.09	43.72	[61]
4.99	1.09	1.09	32.23	18.94	0.63	0.02	10.63	[62]
0.94	-	0.46	-	-	-		-	[63]
0.8	0.1	0.2	58.1	0.1	-	0.1	-	[64]
62.48	18.72	6.54	4.83	2.56	-	-	0.48	[65]
0.48	0.17	0.12	55.09	0.4	0.2	0.06	43.48	[66]
28.35	0.42	9.7	40.45	16.25	-	-	-	[67]
8.38	0.67	0.65	61.83	14.36	0.6	0.33	13.02	[68]
4.99	1.09	1.09	32.23	18.94	0.63	0.02	40.63	[69]
-	0.7	0.33	51.49	0.36	0.19	0.1	44.6	[70]
1.29	0.39	0.78	52.46	0.54	-	-	-	[71]
-	-	0.67	55.45	-	-	-	43.58	[72]

3. Literature Review

In the work of Anitha Selvasofia et al. [60], wet marble sludge was dried and sieved through a 1 mm sieve for use as fine sand in concrete. Marble powder replaced fine aggregates at rates of 0%, 10%, 20%, 30%, 40%, and 50% by weight, with a constant water/cement ratio of 0.5. The mix included 43-grade Portland cement, with fine and coarse aggregates, and was tested using 150 × 150 × 150 mm cubes, 150 mm diameter × 300 mm height cylinders, and 500 × 100 × 100 mm prisms. Optimal results were achieved at 10% marble powder replacement, with compressive strength increasing by 15.04% at 7 days and split tensile strength by 30.73% at 14 days. Beyond 10%, the mechanical properties declined due to water scarcity and finer particle size. Workability improved by 14.28% at 10% but dropped by 33.33% at 50%. The study highlighted the benefits of marble powder for mechanical performance, sustainability, and cost-effectiveness up to 10%, with diminishing returns at higher replacement levels.

In the work of Rashid Ali Kanhar et al. [61], locally sourced fine and coarse aggregates were oven-dried, and marble powder partially replaced cement at rates of 5% and 10% by weight. A constant water/cement ratio of 0.48 was maintained, using CEM I cement, fine aggregates (<4.75 mm), and coarse aggregates (4.75–20 mm). M30 concrete was tested using 150 × 150 × 150 mm cubes for compressive strength (BS EN 12390-3) [73] and 50 × 10 × 10 cm prisms for flexural strength (BS EN 12390-5) [74]. The results showed that marble powder improved workability and enhanced compressive and flexural strength at 90 days, with compressive strength increasing by 16.65% (5%) and 17.27% (10%), and flexural strength by 12.54% (5%) and 1.14% (10%), respectively. The 5% replacement yielded the best early and long-term performance, while replacements above 10% reduced strength gains. Marble powder acted as a low-level superplasticizer, improved long-term mechanical properties, and offered environmental and economic benefits by reducing cement use and waste disposal. However, early strength reductions were noted, warranting further durability studies.

Marco Lezzerini et al. [75] used marble powder as a partial replacement for Portland cement in mortar mixes at rates of 5%, 10%, 15%, 20%, and 25%, with a constant water/cement ratio of 0.5. The mix included standardized sand, demineralized water, and a superplasticizer (MasterGlenium SKY 698). Marble powder was dried for 48 h before use, and mortar specimens (40 × 40 × 160 mm) were tested according to European standards (EN 933-1 [76], EN 933-2 [77], EN 15801 [78], EN 13755 [79], EN 1015-10 [80], EN 1015-11 [81], and EN 12504-4 [82]). The results showed a reduction in compressive strength, with the highest drop at 25% replacement (43.3 MPa, a 26.1% decrease from the reference 58.6 MPa). Strength loss began at 15% (49.8 MPa), but values remained acceptable up to 20%. Water absorption increased slightly from 4.6% to 5.5%, indicating reduced durability at higher replacement levels. Despite mechanical and durability limitations, marble powder contributed to environmental sustainability by reducing waste and CO_2 emissions, offering economic benefits through waste reuse. Further improvements are needed for broader applications.

In the study by Ashish Shukla and Nakul Gupta [62], marble dust powder partially replaced cement in M25 and M30 grade concrete at 0%, 5%, 7.5%, 10%, 12.5%, 15%, and 20%, with a constant water/cement ratio. The mix included 43-grade OPC, river sand, and coarse aggregates (10 mm and 20 mm). Compressive and split tensile strength tests were conducted on cubes and cylinders after 7, 28, and 56 days of curing. The results showed that compressive strength improved for up to 10% replacement, reaching 37.16 MPa (M25) and 43.97 MPa (M30) at 56 days. Beyond 10%, the strength declined, dropping to 29.57 MPa (M25) and 35.80 MPa (M30) at 20% replacement. Split tensile strength followed a similar trend, peaking at 4.85 MPa (M25) and 4.72 MPa (M30) at 10% replacement. While 10% marble dust provided optimal strength improvements, higher replacement levels reduced workability. The study highlighted the environmental benefits, such as reduced cement use and CO_2 emissions, and economic advantages, but noted challenges regarding workability and performance at replacement rates above 10%.

Vijayvenkatesh Chandrasekaran [83] investigated the partial replacement of cement with marble powder in M20-grade concrete at rates of 20%, 30%, and 40%. The study found that 30% replacement yielded optimal compressive strengths of 15.54 N/mm^2 (7 days), 25.56 N/mm^2 (14 days), and 31 N/mm^2 (28 days), while 40% replacement resulted in lower strengths. Split tensile and flexural strengths also peaked at 30% replacement, with values of 4.20 N/mm^2 and 10.50 N/mm^2, respectively, at 28 days. Beyond 30%, the strength properties declined significantly, indicating weaker mixes. Marble powder improved workability and promoted environmental sustainability by utilizing industrial waste. The concrete mix had a fixed water/cement ratio of 0.52, with specific gravities of 2.62 (marble powder), 2.55 (fine aggregate), and 2.78 (coarse aggregate), respectively. The study concluded that marble powder can replace up to 30% of cement without compromising the mechanical properties, offering economic and ecological benefits.

Gopi, R. et al. [84] used marble powder (MP) as a partial cement replacement in M30-grade concrete at 0%, 5%, 10%, 15%, 20%, and 25%, with a constant water/cement ratio of 0.45. The mix included river sand, blue granite jelly (max. 20 mm), and potable water. The cement content was reduced from 426.67 kg/m^3 (control) as the MP increased. The specimens (150 mm cubes, 150 $\times$ 300 mm cylinders, and 100 $\times$ 100 $\times$ 500 mm beams) were tested. The results showed that up to 15% MP replacement improved compressive strength by 14.53% and tensile strength by 14.25% after 28 days, with peak values of 44.62 N/mm^2 (compressive) and 5.13 N/mm^2 (tensile). Flexural strength peaked at 6.28 MPa. Beyond 15%, the workability and strength declined, with mix consistency becoming problematic. The study highlighted the enhanced mechanical properties, durability, and environmental benefits due to reduced cement use, but noted reduced workability at higher MP levels. The findings support MP as a sustainable and economical cement substitute in rates of up to 15%.

Dr. B. Krishna Rao [85] investigated the use of waste marble powder as a partial cement replacement in normal compacting concrete at 0%, 5%, 10%, 15%, and 20%, with a constant water/cement ratio of 0.46. The mix included 53-grade OPC, river sand, and 20 mm crushed granite. Specimens (150 mm cubes, 150 $\times$ 300 mm cylinders, and 100 $\times$ 100 $\times$ 500 mm prisms) were tested. The results showed that up to 10% replacement improved compressive strength by 2.81% (7 days), 2.92% (28 days), and 4.58% (56 days). Split tensile strength increased by 0.43% (7 days), 11.6% (28 days), and 5.6% (56 days), while flexural strength rose by 11.22%, 20%, and 14.8% over the same periods. Workability increased with marble powder content, peaking at 20%, but mechanical properties declined beyond 10%. At 15% and 20% replacement, compressive strength decreased by 1.28% and 5.069% (7 days), and split tensile strength dropped by 15.51% and 24.56%, respectively. The study concluded that 10% replacement optimized strength and durability, offering environmental benefits through waste reuse, but higher replacements led to strength loss.

A. Dhanalakshmi and M. Shahul Hameed [86] tested concrete mixes with partial replacement of sharp sand withff marble dust powder (MDP) at 0%, 5%, 10%, 15%, and 20%, using a fixed water/cement ratio of 0.45. The optimal replacement level was 15%, for which compressive strength at 28 days increased by 54.5% (from 22 MPa to 34 MPa) and split tensile strength rose by 12% (from 3.54 MPa to 3.97 MPa). Workability, measured by slump tests, peaked at 25 mm with 15% MDP. Mix 4 (15% MDP) showed the highest modulus of elasticity (29.15 GPa), indicating improved mechanical properties. The use of MDP also reduced marble waste disposal issues, enhancing sustainability. Beyond 15%, strength properties declined, suggesting 15% as the optimal replacement level for performance and environmental benefits.

Amit Kumar Sharma et al. [63] partially replaced cement with marble dust powder (MDP) at 0%, 5%, 10%, 15%, and 20% in self-compacting concrete (SCC), maintaining a constant water/cement ratio. The mix included 43-grade OPC, river sand, 10 mm and 20 mm coarse aggregates, and potable water. The specimens (150 mm cubes for compressive strength and 150 × 150 × 500 mm beams for flexural strength) were cured for 7, 14, and 28 days and tested according to Indian Standards (IS 456-2000 [87], IS 516-1959 [88], IS 8112-1989 [89], IS 10262:2009 [90], IS 12269:2013 [91]). The results showed that 10% MDP replacement optimized compressive strength, increasing it by 17% (from 24.45 N/mm^2 to 28.65 N/mm^2) at 28 days, with marginal flexural strength improvement. Beyond 10%, compressive strength dropped to 21.05 N/mm^2 (15%) and flexural strength to 3.00 N/mm^2. Workability remained unaffected. The study concluded that MDP enhances mechanical properties and reduces waste and costs at up to 10% replacement, but higher percentages negatively impact performance.

Animesh Mishra et al. [64] replaced cement with marble dust in concrete at rates of 0%, 2.5%, 5%, 7.5%, and 10%, with a w/c ratio of 0.46. The mix included 43-grade OPC, sand, aggregates, and potable water, with a proportion of 1:1.5:3 (cement–sand–aggregate). Compressive strength tests were conducted on 150 mm cubes, showing a 39% increase at 10% replacement (39.89 N/mm^2 at 28 days) compared to the results for the control. Flexural strength also improved incrementally up to 10% replacement. Beyond 10%, the strength began to decline. The study concluded that marble dust enhances mechanical properties up to 10%, reduces waste, conserves resources, and mitigates environmental degradation.

G. AshaLakshmi and P. Sai Pravallika [92] studied the effects of partially replacing cement with metakaolin and marble dust in concrete mixes at rates of 5%, 7.5%, 10%, 12.5%, and 15%, maintaining a water/cement ratio of 0.45. The mix included 53-grade OPC, local sand, and 20 mm coarse aggregate. Optimal results were achieved at 10% replacement for both materials, with compressive strength reaching 41.28 MPa at 28 days (compared to 33.67 MPa for the control). Split tensile strength (4.73 MPa) and flexural strength also peaked at 10%, alongside improved workability. Beyond 10%, all properties declined. The study concluded that 10% replacement optimizes mechanical performance, offering economic and environmental benefits, while higher percentages reduce effectiveness.

Md Mahboob Ali and Prof. S. M. Hashmi [65] investigated the replacement of cement with MP (5%, 10%, 15%, 20%) and sand with stone dust (10%, 20%, 30%) in grade M30 concrete, with a w/c ratio of 0.39. The mix included 491 kg cement, 512.62 kg fine aggregate, and 1186 kg coarse aggregate. The specimens (150 mm cubes, 150 × 300 mm cylinders, and prisms) were tested for mechanical and environmental performance. The results showed that 10% marble powder replacement optimized compressive strength (14.14% increase), split tensile strength (19.61% increase), and flexural strength (10.73% increase). Beyond 10%, the strength declined and workability decreased, requiring the addition of extra water. The study concluded that the rates of 10% marble powder and 20% stone dust were optimal, offering environmental benefits but posing challenges in regards to workability at higher replacement levels.

In this study [66], marble dust powder (MDP), sieved through 90-micron mesh, was used to partially replace cement at rates of 5%, 10%, 15%, and 20%, with a constant water/cement ratio of 0.43. The mix included fine river sand and coarse aggregates (60% 20 mm, 40% 10 mm). The cement content decreased from 445.58 kg to 356.46 kg at 20% replacement, while fine and coarse aggregates remained unchanged. The specimens (cubes, 150 × 300 mm cylinders, and beams) were tested for compressive, split tensile, and flexural strength. The results showed that compressive strength increased by 8.05% at 10% replacement (35.85 MPa at 28 days), while split tensile and flexural strength peaked at 15% replacement (9.21% and 7.5% increases, respectively). Beyond 15%, these properties declined. The study concluded that MDP improves mechanical properties and reduces environmental impact at rates of up to 10–15% replacement, but workability decreased with higher MDP content, leading to stiffer mixes.

Chandrakar and Singh [93] studied the effects of replacing cement with marble dust powder at 5%, 10%, 15%, 20%, 25%, and 30% in M-20 grade concrete. The mix included Portland pozzolana cement, crushed granite (max. 20 mm, specific gravity 2.64), natural sand, and water. Cubes of 150 mm in size were cast and tested for compressive strength at 7 and 28 days. The results showed that 10% replacement yielded the highest compressive strength (29.92 N/mm^2 at 28 days, up from 24.73 N/mm^2 for the control). Beyond 10%, the strength declined, dropping to 18.07 N/mm^2 at 30% replacement. The study concluded that 10% replacement optimized compressive, split tensile, and flexural strengths, while higher replacements reduced mechanical performance and workability, increasing water demand. The environmental benefits included reduced cement consumption, improved sustainability, and cost savings.

Majeed et al. [94] used waste marble powder (WMP) to replace cement at rates of 0%, 5%, 10%, 15%, and 20% by weight in concrete mixes with a constant water/cement ratio of 0.45. The mix proportion was 1:1.5:3, using ordinary Portland cement, river sand, and coarse aggregates. The specimens (beams and cylinders) were tested for their destructive and non-destructive properties. The results showed that 10% WMP replacement yielded the highest compressive strength (31.8 MPa at 28 days, a 25.6% increase over the control at 25.3 MPa). Workability decreased with a higher WMP content due to increased water absorption, although finer WMP particles improved concrete compactness. Beyond 10%, compressive, tensile, and flexural strengths declined due to weaker cement paste bonding. The study highlighted the environmental benefits, such as reduced cement use and waste recycling, but noted challenges regarding workability and strength at replacements levels above 10%.

Sharma et al. [95] used OPC-53 cement, local river sand, marble dust, and stone aggregates to prepare concrete. Marble dust partially replaced cement and fine aggregate at 5%, 10%, and 15%, with a constant water/cement ratio of 0.5. The control mix (M-25) had a proportion of 1:1:2. Compressive strength tests conducted on cubes over 3, 7, 14, 21, and 28 days showed that 5% and 10% cement replacement increased the strength, peaking at 23.72 N/mm^2 (5%) at 28 days, while 15% replacement decreased the strength to

19.28 N/mm^2. When marble dust replaced fine aggregates, compressive strength peaked at 30.64 N/mm^2 (15% replacement). Workability, tested via slump, improved slightly (55 mm to 65 mm) with higher marble dust content. The study concluded that marble dust enhances the mechanical properties within a certain threshold, offering economic and environmental benefits by reducing cement use and solid waste disposal. However, the mechanical properties declined at higher replacement levels.

Shirule et al. [96] studied MP as a cement replacement in concrete and mortar at rates of 5% to 15%, with a water/cement ratio of 0.5. The mix included cement, coarse and fine aggregates, and water. The specimens (150 mm cubes and 150 × 300 mm cylinders) were tested, showing significant improvements in mechanical properties, i.e., compressive strength increased by 10% (10% replacement), split tensile strength by 5%, and flexural strength by 7%. Workability decreased with higher marble powder content, especially beyond 15%, where the benefits diminished. The study highlighted the environmental advantages, such as reduced cement consumption and waste, but noted challenges in maintaining optimal workability. Durability, particularly resistance to sulfate attacks, improved, offering economic benefits through material cost savings.

Pal et al. [97] replaced cement with marble dust powder at rates of 0%, 5%, 10%, 15%, 20%, 25%, and 30% in M20-grade concrete, with a constant water/cement ratio of 0.5. The mix included fine and coarse aggregates (specific gravities 2.64 and 2.81) and followed a 1:1.5:3 proportion. The specimens (150 mm cubes and 150 × 300 mm cylinders) were tested. The results showed that up to 10% replacement improved compressive strength by 8.54% (7 days) and 12.84% (28 days), and split tensile strength by 15.55% and 17.95%, respectively. Beyond 10%, compressive strength dropped by 36.23% at 30% replacement. The study concluded that marble dust optimized the mechanical properties and durability at optimal levels, offering economic and environmental benefits. However, higher replacements reduced workability and strength.

Vaidevi C. [67] studied marble dust as an additive in cement concrete, replacing cement at rates of 5%, 10%, 15%, and 20%, with a water/cement ratio of 0.47. Tests for compressive and tensile strength were conducted at 14 and 28 days. The results showed that 10% replacement yielded the highest compressive strength (38.17 MPa at 28 days), while higher replacements (15%, 20%) led to strength loss. Tensile strength also peaked at 10% (2.5 MPa). Marble dust improved workability, reduced environmental impact, and saved cement (at a rate of 1 bag per 10 bags). However, the drawbacks included reduced mechanical properties at higher replacement levels and variability in durability with curing time.

Singh et al. [98] replaced cement with marble powder at rates of 10%, 15%, 20%, and 25%, using water-to-binder ratios of 0.35, 0.40, and 0.45. The mix included crushed basalt (coarse aggregate), crushed sand (fine aggregate), and Glenium B233 superplasticizer for workability. The specimens were tested for long-term compressive, tensile, and flexural strength, water permeability, abrasion resistance, and sorptivity. The results showed that 15% replacement increased compressive strength by 4.6% (28 days), tensile strength by 6%, and reduced water permeability and sorptivity by 4%, enhancing durability. However, higher replacements reduced mechanical performance, with up to 20% compressive strength loss. The study concluded that 10–15% marble powder replacement optimized strength and durability, while higher percentages adversely affected concrete properties.

Zhang et al. [68] studied the effects of silica fume (SF) and waste marble powder (WMP) on the mechanical and durability properties of cellular concrete. The mix included Portland cement, SF (0–10%), WMP (5–20%), coarse aggregate ($\leq$10 mm), fine river sand, and a polycarboxylate superplasticizer, with a constant water/binder ratio of 0.33. The specimens (150 × 150 × 150 mm cubes) were tested. The results showed that 10% SF and 5% WMP yielded optimal mechanical properties, with compressive strength increasing by 19.8% (56.14 MPa) and splitting tensile strength by 20%. Higher WMP replacements reduced strength due to lower calcium compound levels. Durability improved, with reduced water absorption and enhanced sulfate resistance at 10% SF and up to 20% WMP, but declined at higher percentages. The study highlighted the environmental and economic benefits, such as industrial waste utilization and sustainability, while maintaining mechanical strength.

Chavhan and Bhole [69] added marble powder to sand in M25-grade concrete at replacement levels of 0% to 50%, with a constant water/cement ratio of 0.45. The mix included cement (specific gravity 3.15), marble powder (specific gravity 2.84), fine aggregates, and coarse aggregates. The specimens (150 mm cubes and cylinders) were tested. The results showed that up to 45% replacement, compressive strength increased by 20.6% (34.08 N/mm^2 at 28 days), and split tensile strength reached 5.86 N/mm^2, with improved workability and mechanical properties. Beyond 45%, the strength slightly declined, and at 50%, the properties decreased, highlighting challenges regarding workability and durability. The study concluded that marble powder offers environmental and economic benefits at optimal replacement levels but poses limitations at higher percentages.

Rishi and Aggarwal [99] studied the partial replacement of fine aggregate and cement with waste marble powder (WMP) in M25-grade concrete, using a water/cement ratio of 0.43. The mix included 43-grade OPC, fine aggregate, and WMP. Four mixes were prepared, i.e., 10% sand replacement, 10% cement replacement, and 20% WMP (10% sand + 10% cement). Flexural and split tensile strengths were tested at 7 and 28 days. The results showed that 10% WMP replacement (cement or sand) improved flexural strength by 5% (sand) and 2% (cement), and split tensile strength by 12% and 11%, respectively. However, 20% replacement caused an 11% reduction in both strengths. The study concluded that 10% WMP replacement optimized mechanical properties, while higher replacements led to strength loss.

Sounthararajan and Sivakumar [70] partially replaced cement with marble powder in concrete at rates of 0% to 15%, with a water/cement ratio of 0.3 and a fine/cement ratio of 0.6. The mix included OPC, river sand, 20 mm coarse aggregate, and a polycarboxylic ether-based superplasticizer. The results showed that 10% replacement increased compressive strength by 12% (49.3 MPa at 28 days), split tensile strength by 24.29% (4.35 MPa), and flexural strength by 16.9% (4.21 MPa). Beyond 10%, the strength declined, with the lowest strength noted at 15%. Workability decreased with higher marble powder content, requiring the addition of superplasticizers. The study concluded that 10% marble powder replacement optimized mechanical properties, without compromising workability.

Latha et al. [100] used 53-grade OPC, river sand, and 20 mm coarse aggregate, with waste marble powder (WMP) sieved to a size of 90 microns as a cementitious material. The water/cement ratio varied from 0.41 to 0.53 for the M20, M30, and M40 concrete grades. WMP replaced cement at 0%, 5%, 10%, 15%, and 20%, and the specimens (cubes, cylinders, prisms) were tested after 7 and 28 days of curing. The results showed that up to 10% WMP improved compressive, tensile, and flexural strengths, with compressive strength peaking at 38.36 MPa (M20) and flexural strength at 5.17 MPa (15% replacement). Beyond 15%, WMP acted as an inert filler, reducing strength. The study highlighted the improved mechanical properties, workability, and durability up to 15%, along with environmental benefits like reduced costs and pollution. However, higher replacements led to strength loss.

Ofuyatan et al. [71] used OPC 42.5 grade, sharp sand, 12.5 mm granite, and potable water, with marble dust powder replacing sand at rates of 0%, 15%, 25%, and 35%. The mix proportion was 1:2:4, and 36 cubes (150 × 150 × 150 mm) were tested. The results showed that 25% replacement improved workability (25 mm slump) and increased compressive strength by 11% (32.8 MPa at 56 days) and split tensile strength by 17.95% (28 days). The study concluded that 25% marble dust replacement optimized mechanical performance, offering sustainability and cost benefits. However, replacements above 25% reduced compressive strength.

Ghani et al. [72] investigated the replacement of sand with waste marble powder (WMP) in concrete at rates of 0%, 20%, 40%, 60%, and 80%, with a constant water/cement ratio of 0.62 (ASTM). The results showed that workability and bulk density decreased with WMP, while compressive strength increased up to 40% replacement (45% improvement at 70 days) but declined thereafter. Split tensile strength improved slightly at 20% but decreased at higher replacement rates. Water permeability decreased consistently up to 60% WMP, enhancing durability, but increased slightly at 80%. The study highlighted the environmental benefits and improved compressive strength and durability with the addition of WMP, although higher replacement levels reduced workability and strength.

Khodabakhshian et al. [101] prepared 16 concrete mixes with varying percentages of marble waste powder (MWP: 0%, 5%, 10%, 20%) and silica fume (SF: 0%, 2.5%, 10%, 15%), maintaining a water/binder ratio of 0.45. The mix included crushed gravel, river sand, polycarboxylate ether superplasticizer, and water, designed as per ACI 211.1. The specimens (100 mm cubes and cylinders) were tested at various intervals. The results showed that 5% MWP and 10% SF improved compressive strength by 18.5% at 56 days, while tensile strength increased by 12–17% with moderate replacements. Higher MWP percentages reduced strength and workability. The study concluded that 5–10% MWP and 10% SF optimized mechanical properties, durability, and environmental benefits, balancing strength, workability, and cost-effectiveness.

Table 3 summarizes the key findings for marble powder subjected to freeze–thaw cycles, high-temperature exposure, and acid resistance conditions from several research papers.

Table 3. Key findings for a unique state of marble powder under freeze–thaw, high-temperature, and acid resistance conditions.

Major Findings	Discussion and Results	Advantages and Limitations	[Ref.]
Splitting tensile strength increase: 8.33–13.9% Water absorption reduction: ~20.34% Abrasion loss reduction: 7.9–14.8 $cm^3/50\ cm^2$ Freeze–thaw mass loss reduction: 0.34–0.57 kg/m^2	The study explored using marble powder as a full replacement for aggregates in interlocked paving stones. Results showed that marble-based stones displayed better mechanical properties, such as higher tensile strength and lower water absorption, compared to those of traditional concrete. A special curing method further improved durability and freeze–thaw resistance. The findings highlight marble powder as a sustainable construction material, offering an eco-friendly solution to reduce marble waste pollution.	Advantages: Improved durability: the use of marble powder and Ahlat stone powder in concrete paving stones improved durability and freeze–thaw resistance. Sustainable waste utilization: the study demonstrated the effective use of waste materials (marble powder and Ahlat stone powder) in construction, reducing environmental pollution. Enhanced mechanical properties: the special curing method increased splitting tensile strength, reduced water absorption, and improved abrasion resistance. Cost-effectiveness: the use of locally available waste materials reduced production costs. Limitations: Abrasion loss: compared to paving stones that underwent conventional water curing, those that underwent combination curing displayed a greater abrasion loss, indicating potential surface damage over time. Freeze–Thaw resistance: while freeze–thaw resistance improved, the mass loss was higher for some mixes, especially at higher temperatures (above 400 °C). Limited application: the study focused on paving stones, and the findings may not directly apply to other structural concrete applications. Long-term durability: The long-term performance of the paving stones under extreme weather conditions and heavy traffic requires further investigation.	[102]

Table 3. *Cont.*

Major Findings	Discussion and Results	Advantages and Limitations	[Ref.]
Compressive strength: Marble dust and foundry sand can replace up to 10% of cement and fine sand, respectively, improving compressive strength by 10.7% at ambient temperature (29 °C). At temperatures as high as 400 °C, strength increased by 21.5% (annealing) and 16.3% (quenching). However, strength decreased by 52.5–54.8% at temperatures above 600 °C. Flexural strength: Flexural strength increased by 12.7% (annealing) and 15.6% (quenching) at 400 °C with 5–10% replacement. It decreased by 40–51.7% at temperatures above 600 °C. Tensile strength: Tensile strength increased by 31.1% (annealing) and 16.9% (quenching) at 400 °C with 10% replacement. It decreased by 52.5–53.3% at temperatures above 600 °C. Elastic modulus: static and dynamic elastic moduli decreased significantly at 1000 °C, with reductions of 77.4–86.9% and 76–94.1%, respectively, for marble dust and foundry sand concrete. Water absorption: water absorption increased by three times at 1000 °C, indicating rapid degradation due to the formation of large voids. Mass loss: mass loss was minimal up to 400 °C, but elevated by 40.7% at 600 °C and beyond due to water evaporation and void formation. Ultrasonic pulse velocity (UPV): UPV decreased with rising temperatures but remained above 3.2 km/s up to 600 °C, indicating acceptable concrete quality.	The study demonstrated that replacing up to 10% of cement, fine sand, marble dust, and foundry sand improved the mechanical properties of concrete at temperatures of 400 °C or higher. But above 400 °C, the concrete degraded rapidly, especially with higher replacement levels (15–20%). The degradation was attributed to the collapse of the C-S-H gel, the formation of voids, and the evaporation of chemically bound water. Quenching caused more significant strength loss compared to annealing due to thermal shock and rapid cooling. The findings suggest that marble dust and foundry sand can be used as sustainable materials in concrete, but their performance is limited at high temperatures.	Advantages: Improved compressive strength and sorptivity when blending OPC with marble dust (MD) and fine kaolinite sand (FKS). Enhanced resistance to sulfuric acid attack, especially with 10% MD. Sustainable use of industrial waste (MD and FKS) reduced environmental pollution. Formation of denser microstructures and secondary hydration products improves durability. Limitations: Reduced resistance to acetic acid attack, especially after 6 months of immersion. Blends with both MD and FKS showed lower resistance to acid attack due to reduced calcium hydroxide (CH) content. Performance under acidic conditions is not fully optimized, requiring further research.	[103]
Compressive strength: Blending OPC with 5–20% marble dust (MD) improved compressive strength, with the best results at 5% MD. Blending OPC with both MD and fine kaolinite sand (FKS) also enhanced strength, particularly with 10% MD and 5% FKS. Water absorption: Water absorption decreased with curing time, indicating denser structures. Mixes with 5–20% MD showed lower water absorption, especially at 20% MD. Acid resistance: OPC pastes with 10% MD exhibited the highest resistance to sulfuric acid, while acetic acid caused significant deterioration after 6 months for all mixes. Microstructure: SEM and XRD analyses confirmed the formation of denser structures and secondary hydration products in MD and FKS blends, improving mechanical properties.	The study demonstrated that marble dust (MD) and fine kaolinite sand (FKS) can enhance the mechanical and durability properties of OPC pastes. MD acted as a filler, refining the pore structure and accelerating hydration, while FKS contributed to the formation of secondary calcium silicate hydrates (CSHs), improving strength and durability. However, blends with both MD and FKS showed reduced resistance to acid attack due to lower calcium hydroxide (CH) content. The findings suggest that MD and FKS can be effectively used as sustainable additives in cement, but their performance under acidic conditions requires further optimization.	Advantages: Improved mechanical properties (compressive, flexural, and tensile strength) with up to 10% marble dust and foundry sand are used in place of cement and fine sand, respectively. Enhanced resistance to elevated temperatures up to 400 °C. Sustainable use of waste materials (marble dust and foundry sand) reduces environmental impact. Combined curing methods (annealing and quenching) improved strength retention. Limitations: Rapid degradation of concrete properties at temperatures above 400 °C, especially with higher replacement levels (15–20%). Quenching caused more significant strength loss compared to annealing due to thermal shock. Limited performance under extreme temperatures (above 600 °C) and long-term durability needs further investigation.	

Table 3. *Cont.*

Major Findings	Discussion and Results	Advantages and Limitations	[Ref.]
Marble dust: increased compressive strength and reduced porosity in cement mortars. Glass fiber: decreased compressive strength and increased porosity due to poor adhesion. High temperature: compressive strength decreased significantly above 400 °C, with porosity increasing due to micro-cracks and dehydration. Optimal mix: the best performance was achieved with 50% marble dust, no glass fiber, and exposure to 20 °C.	Marble dust: Acts as a micro-filler, improving the interface between the aggregate and cement paste, leading to higher strength and lower porosity. Glass fiber: poor adhesion with mortar caused voids, reducing strength and increasing porosity. High temperature: dehydration and micro-crack formation at temperatures above 400 °C led to significant strength loss and increased porosity.	Advantages: Utilization of waste marble dust improves environmental sustainability. Taguchi method reduced the number of experiments, saving time and resources. Limitations: Glass fiber's poor adhesion limits its effectiveness in enhancing mortar properties. High-temperature exposure significantly degrades mortar performance, limiting its use in high-temperature environments.	[104]
Marble Powder (WMP): Adding up to 10% WMP increased compressive and flexural strength in all cement types (OPC, WC, CAC). However, 15% WMP led to a slight decrease in strength. Cement types: Calcium aluminate cement (CAC) showed the highest compressive strength, especially with 10% WMP (104.09 MPa). White cement (WC) and ordinary Portland cement (OPC) exhibited similar strength results. Freeze–Thaw resistance: After freeze–thaw cycles, CAC-based mixtures experienced significant strength loss compared to those of OPC and WC, especially at higher WMP levels (15%). Capillary water absorption: WMP reduced capillary water absorption and sorptivity, with CAC-based mixtures showing the lowest values. However, after freeze–thaw cycles, absorption increased, particularly in CAC mixtures.	Marble powder: WMP acted as a micro-filler, improving the transition zone between the aggregate and cement paste, leading to higher strength and lower porosity. However, at 15% WMP, the reduction in cementing materials (C3S, C2S, C3A) caused a slight decrease in strength. Cement types: CAC exhibited the highest early strength due to its hydration products (CAH10, C2AH8), but its strength loss after freeze–thaw cycles was more pronounced due to phase transformation (CAH10 to C3AH6), which increased porosity. Freeze–Thaw cycles: OPC and WC mixtures showed better resistance to freeze–thaw cycles compared to CAC. The strength loss in CAC mixtures was attributed to the transformation of metastable hydration products, which accelerated under freeze–thaw conditions. Capillary absorption: WMP reduced capillary water absorption and sorptivity by filling pores, but after freeze–thaw cycles, the absorption increased, especially in CAC mixtures, due to the degradation of hydration products.	Advantages: Using WMP as a cement substitute reduces CO_2 emissions and environmental pollution. WMP improves the mechanical properties of mortar, especially at 10% replacement. CAC offers high early strength and is suitable for specific applications like refractory materials. Limitations: CAC-based mixtures showed significant strength loss after freeze–thaw cycles, limiting their use in cold climates. High WMP content (15%) reduced strength due to the decrease in cementing materials. CAC's phase transformation under freeze–thaw conditions increases porosity, reducing durability.	[105]
Superhydrophobic marble powder (SMP): modification of marble powder (MP) with stearic acid (STA) achieved a superhydrophobic state with a water contact angle of 152°. Mortar properties: Adding 20% SMP to mortar resulted in a hydrophobic surface with a water contact angle of 98°, significantly reducing water absorption by 36.42%. Hydration and microstructure: SMP improved cement hydration, leading to a denser microstructure and reduced porosity. Corrosion resistance: mortar with 20% SMP showed enhanced corrosion resistance, with a polarization resistance 4 times higher than ordinary mortar.	Superhydrophobic modification: Stearic acid modification of MP introduced hydrophobic groups (-CH_3 and -CH_2), reducing surface energy and achieving superhydrophobicity. The optimal STA content was 6%. Mortar performance: SMP improved the hydration of cement, increasing the formation of hydration products like C-S-H and ettringite, which enhanced the mortar's mechanical properties and reduced porosity. Water absorption: The addition of SMP significantly reduced water absorption, with the 20% SMP mix showing the lowest absorption rate. This is attributed to the hydrophobic nature of SMP and the improved pore structure. Corrosion resistance: the hydrophobic barrier created by SMP reduced water infiltration, making it difficult for chloride ions to penetrate the mortar, thus improving corrosion resistance.	Advantages: Utilizes waste marble powder, promoting environmental sustainability. Enhances mortar's water repellency and corrosion resistance, making it suitable for offshore environments. Improves cement hydration and reduces porosity, leading to better mechanical properties. Limitations: The process of modifying MP with stearic acid adds complexity to mortar preparation. High SMP content (20%) is required to achieve significant hydrophobicity, which may affect the mortar's workability and cost. Long-term durability and performance under real-world conditions require further investigation.	[106]

4. Comparative Analysis

Previous studies have reviewed the use of MP and WMP as partial replacements for cement and fine aggregates in concrete mixes. In each, different replacement percentages were tested, along with water/cement ratios ranging from 5% to 50%, to study the effects on compressive strength, split tensile strength, flexural strength, and workability. In general, the trend of the test results indicated that up to 10–15% replacements of MP improved the mechanical properties, specifically strength and workability, of concrete; at the other extreme, replacement beyond this percentage reduced strength and imposed some problems concerning workability. The environmental benefits include the reduction of cement usage and waste recycling, as it is used for mortars and bricks [6,107–110]. However, durability problems increased at high replacement levels. These various studies have concluded that moderate replacements result in the sustainability enhancement of concrete, with improved performance and economic benefits.

Figure 3 illustrates a comparison of compressive strength in the range at which concrete gains most of its strength at 28 days of curing at different percentages of MP, i.e., MP0, MP5, MP10, MP15, and MP20, recorded by various researchers. The compressive strength recorded in the individual works is quite high. According to the data shown in Table 4, among them, the results of Dr. B. Krishna Rao [85] are the highest, amounting to 46.22 MPa. In the case of concrete with 5% replacement, MP5, the majority of the research investigated showed slight increases; the peak in strength was 46.5 MPa, although some researchers found a slight drop in strength. The compressive strength is the highest at 10% replacement, MP10, where a number of researchers record their highest values, including the highest value recorded by Dr. B. Krishna Rao at 47.55 MPa, which suggests that this may be an optimal replacement level for improvement in the properties of concrete. At 15% and 20% replacement, a number of researchers show that compressive strength begins to decline, which basically tells us that beyond this limit, the returns on strength become slight or even negative. The chart indicates that, as a whole, replacement levels up to 10–15% improve strength, while higher percentages reduces compressive strength [60,63,65–67,84,85,93,94,96,97].

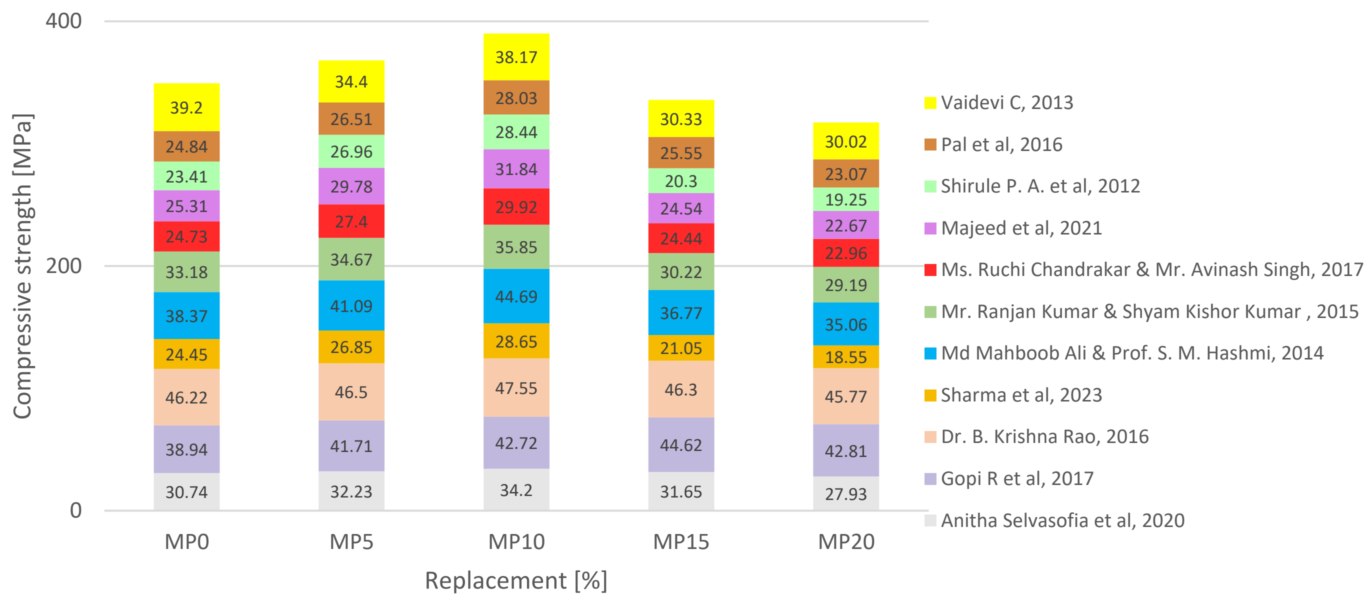

Figure 3. Compressive strength of concrete at different [%] of MP [60,63,65–67,84,85,93,94,96,97].

Table 4. Compressive strength test data at various percentages of MP [%] from the different references shown in Figure 3.

Reference	MP0	MP5	MP10	MP15	MP20
Anitha Selvasofia et al. [60]	30.74	32.23	34.2	31.65	27.93
Gopi, R. et al. [84]	38.94	41.71	42.72	44.62	42.81
Dr. B. Krishna Rao [85]	46.22	46.5	47.55	46.3	45.77
Sharma et al. [63]	24.45	26.85	28.65	21.05	18.55
Md Mahboob Ali and Prof. S. M. Hashmi [65]	38.37	41.09	44.69	36.77	35.06
Mr. Ranjan Kumar and Shyam Kumar [66]	33.18	34.67	35.85	30.22	29.19
Ms. Ruchi Chandrakar and Mr. Singh [93]	24.73	27.4	29.92	24.44	22.96
Majeed et al. [94]	25.31	29.78	31.84	24.54	22.67
Shirule, P. A. et al [96]	23.41	26.96	28.44	20.3	19.25
Pal et al. [97]	24.84	26.51	28.03	25.55	23.07
Vaidevi, C. [67]	39.2	34.4	38.17	30.33	30.02

The chart in Figure 4 and values in Table 5 represent these references because they share the same curing time of 28 days and replacement percentages of 0, 5, 10, 15, and 20, while no replacement exhibits lower compressive strength compared with other replacement percentages, in particular for Gopi, R. et al., whose peak strength lies at MP20. The marble powder replacement of 20% MP20 yielded considerably improved compressive strength when compared to its counterpart with no replacement, MP0. In this regard, for Selvasofia, S.D. and Sarath, V. and Sharma, A.K., whereas strengths at MP0 are not as low in the work of Gopi, R., et al., they still realize better results at MP10 or MP20, showing that a certain percentage of marble powder replacement enhances concrete strength over time. The general observation is that partial replacement with marble powder can enhance compressive strength, especially with replacement percentages at higher values, such as MP10 or MP20, while MP0 (no replacement) leads to lower results, in most cases [60,63,84].

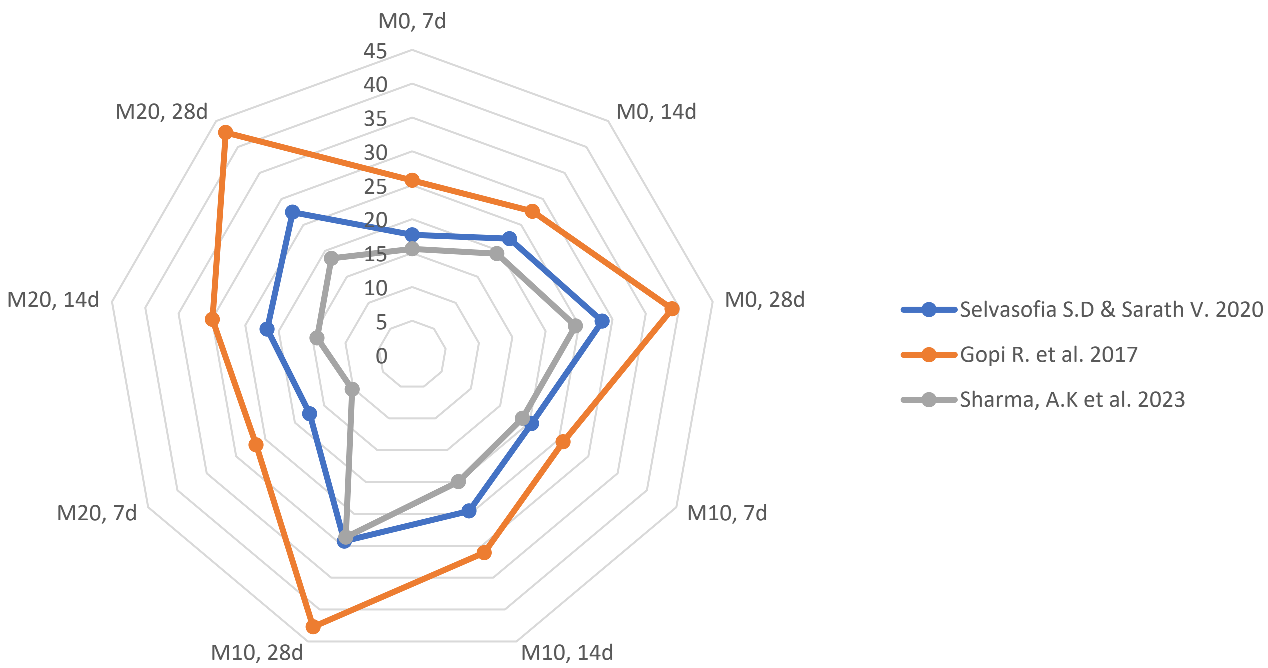

Figure 4. Standard 7-, 14-, and 28-day concrete compressive strength tests [60,63,84].

Table 5. Compressive strength test data at various percentages of MP [%] from the different references shown in Figure 4.

Ref	M0, 7 d	M0, 14 d	M0, 28 d	M10, 7 d	M10, 14 d	M10, 28 d	M20, 7 d	M20, 14 d	M20, 28 d
Selvasofia, S.D., and Sarath, V. [60]	17.68	22.34	28.47	20.34	24.54	29.27	17.46	21.73	27.46
Gopi, R. et al. [84]	25.72	27.61	38.94	25.72	31.09	42.72	26.59	29.93	42.81
Sharma, A.K. et al. [63]	15.62	19.45	24.45	18.78	19.94	28.65	10.22	14.25	18.55

Singh et al. employed a better approach, as shown in Figure 5 and Table 6, when they evaluated the MP not only under different replacement percentages and curing times, but also with different w/c ratios, using 0.35, 0.4, and 0,45, providing a better holistic view. The compressive strength of the concrete with different w/c ratios and marble powder replacement percentages is shown in this chart, after curing times of 28, 56, 90, 180, and 360 days. Also, in a w/c ratio of 0.45, increasing the rate of waste marble powder substitution results in improved strength, and M25 concrete attains its best compressive strength of 26.03 MPa on the 360th day. Compressive strength is improved further at a ratio of 0.40 w/c, in which M15 and M25 increase substantially to reach 40.80 MPa and 39.33 MPa at 360 days, respectively. For the 0.35 w/c ratio, the highest strength recorded is for the M15 replacement, with an average value of 47.80 MPa at 360 days, and for M20, the average value is 42.02 MPa. The strength generally tends to improve as the curing time increases across the ratios, thus showing the long-term benefits achieved by marble powder replacement [98].

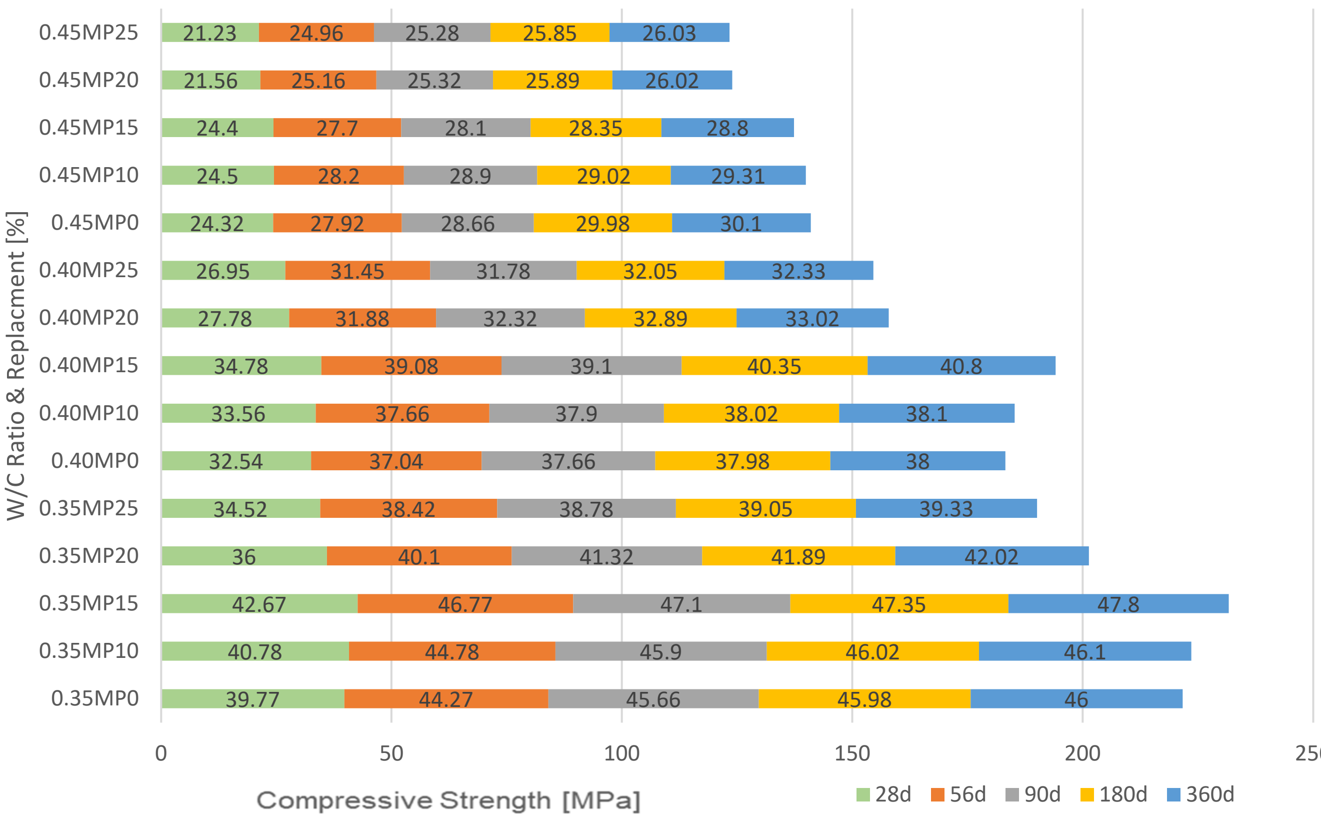

Figure 5. Compressive strength test using different w/c ratios and MP replacements [%] [98].

Table 6. Compressive strength test using the different water/cement ratio shown in Figure 5.

Mix	28 d	56 d	90 d	180 d	360 d
0.35M0	39.77	44.27	45.66	45.98	46
0.35M10	40.78	44.78	45.9	46.02	46.1
0.35M15	42.67	46.77	47.1	47.35	47.8
0.35M20	36	40.1	41.32	41.89	42.02
0.35M25	34.52	38.42	38.78	39.05	39.33
0.40M0	32.54	37.04	37.66	37.98	38
0.40M10	33.56	37.66	37.9	38.02	38.1
0.40M15	34.78	39.08	39.1	40.35	40.8
0.40M20	27.78	31.88	32.32	32.89	33.02
0.40M25	26.95	31.45	31.78	32.05	32.33
0.45M0	24.32	27.92	28.66	29.98	30.1
0.45M10	24.5	28.2	28.9	29.02	29.31
0.45M15	24.4	27.7	28.1	28.35	28.8
0.45M20	21.56	25.16	25.32	25.89	26.02
0.45M25	21.23	24.96	25.28	25.85	26.03

Tensile strengths in MPa at different replacement percentages, from MP0 to MP20, are shown in Figure 6 and Table 7. For MP0, tensile strengths range from the minimum of 2.2 MPa, by Pal et al. to a maximum tensile strength of 4.65 MPa, by Pooja J. Chavhan and Prof. S.D. Bhole. Generally, an increase in the replacement to MP5 results in higher tensile strength, with values falling in the range of 2–4.89 MPa, showing marginal improvement. The MP10 shows a continued incline in the tensile strength, with the highest recorded at 5.13 MPa by G. Asha Lakshmi and P. Sai Pravallika, which may suggest that this could potentially be the optimum level to attain for achieving increased tensile strength. For MP15 (15%), some studies show that the tensile strength remains high, but other studies show that it has started to fall off a little, marking the beginning of the decline of these materials. The percentage of the replacement of MP20 (20%) exhibits a lower value at 1.7 MPa, according to Pal et al., showing that this tendency of replacement percentage has the opposite effect on the enhancement of material strength. Overall, it is found that only a moderate replacement percentage, MP5-MP10, can exhibit improvements in tensile strength while significant reductions are observed for higher values, e.g., MP20 [63,65,66,69,92,94–97].

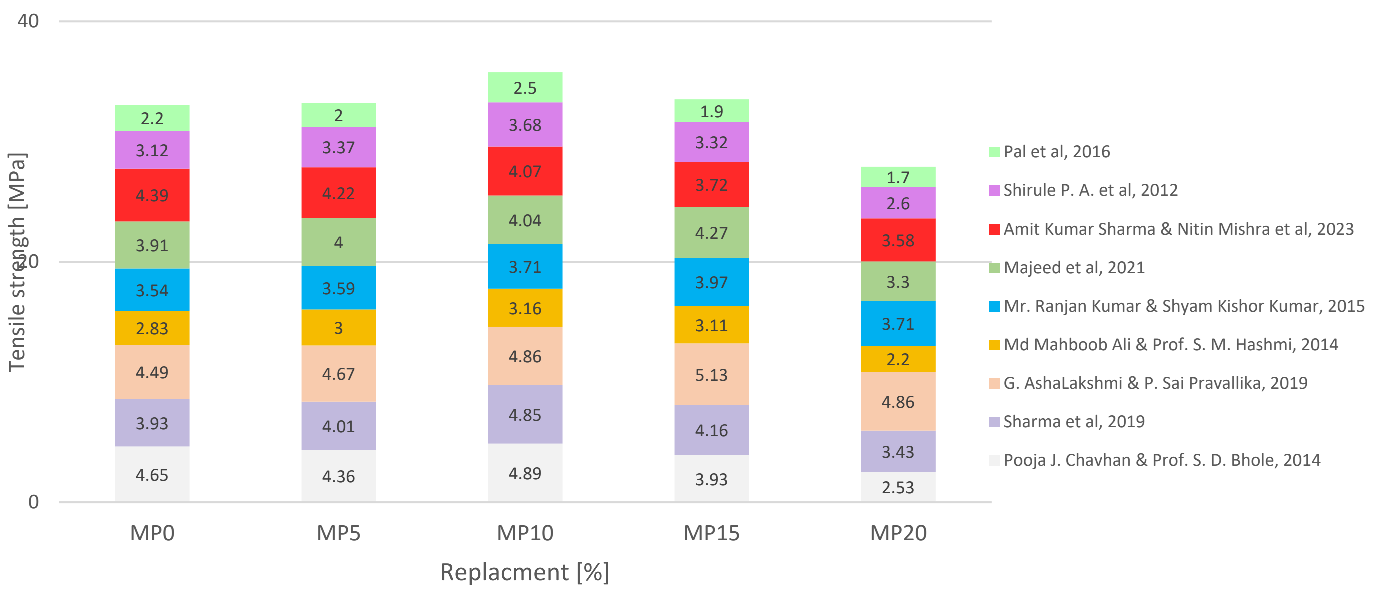

Figure 6. Tensile strength of concrete at differing [%] of MP [63,65,66,69,92,94–97].

Table 7. Tensile strength tests data at various percentages of MP [%] obtained from the different references shown in Figure 6.

References	MP0	MP5	MP10	MP15	MP20
Pooja J. Chavhan and Prof. S. D. Bhole [69]	4.65	4.36	4.89	3.93	2.53
Sharma et al. [95]	3.93	4.01	4.85	4.16	3.43
G. AshaLakshmi and P. Sai Pravallika [92]	4.49	4.67	4.86	5.13	4.86
Md Mahboob Ali and Prof. S. M. Hashmi [65]	2.83	3	3.16	3.11	2.2
Mr. Ranjan Kumar and Shyam Kishor Kumar [66]	3.54	3.59	3.71	3.97	3.71
Majeed et al. [94]	3.91	4	4.04	4.27	3.3
Amit Kumar Sharma and Nitin Mishra et al. [63]	4.39	4.22	4.07	3.72	3.58
Shirule, P. A. et al. [96]	3.12	3.37	3.68	3.32	2.6
Pal et al. [97]	2.2	2	2.5	1.9	1.7

The following chart in Figure 7 and values in Table 8 present the test results of three studies dealing with performance tests of concrete at mixture percentages of 0, 5, 10, 15, and 20%, amplified with curing for 7, 14, and 28 days, respectively, with respect to tensile strength. Ali Khodabakhshian et al. [101] present the lowest value at 7 days, while MP0 records about 1.0 MPa, presenting a gradual increase up to 28 days, in which MP20 reaches about 3.5 MPa. G. AshaLakshmi and P. Sai Pravallika [92] record the highest performance for MP20 at 28 days, peaking at about 4.0 MPa, while MP10 at 7 days can show as much as an order of magnitude decline, to approximately 0.5 MPa, representing a reduction of 50% in the final strength. The results from Md Mahboob Ali and Prof. S. M. Hashmi [65] are more balanced among all the mix ratios, while MP0 peaks to about 2.5 MPa after 28 days, and MP20 shows similar strength development over time. In summary, all the studies conducted so far have shown 30–50% strength gains between 7 and 28 days, confirming that higher mix ratios and longer curing periods make significant contributions to the improvement in mechanical properties due to marble powder replacement in concrete.

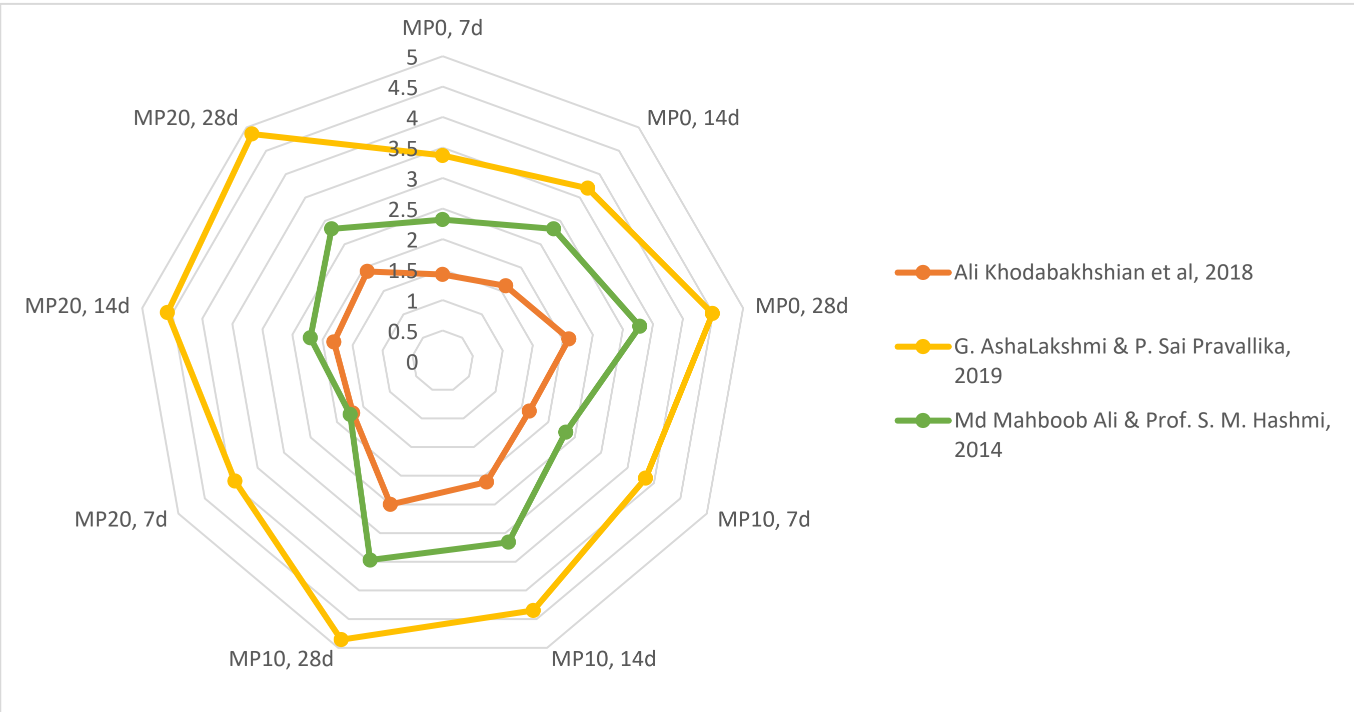

Figure 7. Standard 7-, 14-, and 28-day concrete tensile strength tests [65,92,101].

Table 8. Concrete tensile strength data from studies shown in Figure 7.

References	MP0, 7 d	MP0, 14 d	M0, 28 d	MP10, 7 d	MP10, 14 d	MP10, 28 d	MP20, 7 d	MP2, 14 d	MP20, 28 d
Ali Khodabakhshian et al. [101]	1.42	1.61	2.1	1.64	2.11	2.5	1.7	1.81	1.92
G. AshaLakshmi and P. Sai Pravallika [92]	3.37	3.7	4.49	3.84	4.35	4.86	3.93	4.58	4.86
Md Mahboob Ali and Prof. S. M. Hashmi [65]	2.32	2.83	3.28	2.33	3.16	3.47	1.75	2.2	2.83

Singh et al. [98], as shown in Figure 8 and Table 9, observed the split tensile strength development of concrete for different marble dust replacements (0%, 10%, 15%, 20%) and w/c ratios (0.45, 0.40, 0.35) cured at various ages, i.e., 28, 56, 90, 180, and 360 days. In general, concrete mixes with a w/c of 0.35 exhibit higher tensile strength than that of mix 0.45 for all replacement levels. The optimum tensile strength occurred at 15% marble dust replacement, with the 0.35MP15 mix recording the highest tensile strength of 6.19 MPa after 360 days of curing from an initial 5.7 MPa after 28 days. Generally, strengths have shown a tendency to increase with age, although a marked increase is observed for higher replacement percentages at 180 and 360 days. For instance, the tensile strength of the 0.35MP20 mix increased from 5.5 MPa at 28 days to 6.09 MPa at 360 days, underlining the positive long-term action of marble dust. The results obtained indicate that marble dust replacement, within a replacement percentage range of 15–20% at lower w/c ratios like 0.35, significantly enhances the long-term tensile strength of concrete and hence, has proved to be a promising eco-friendly additive.

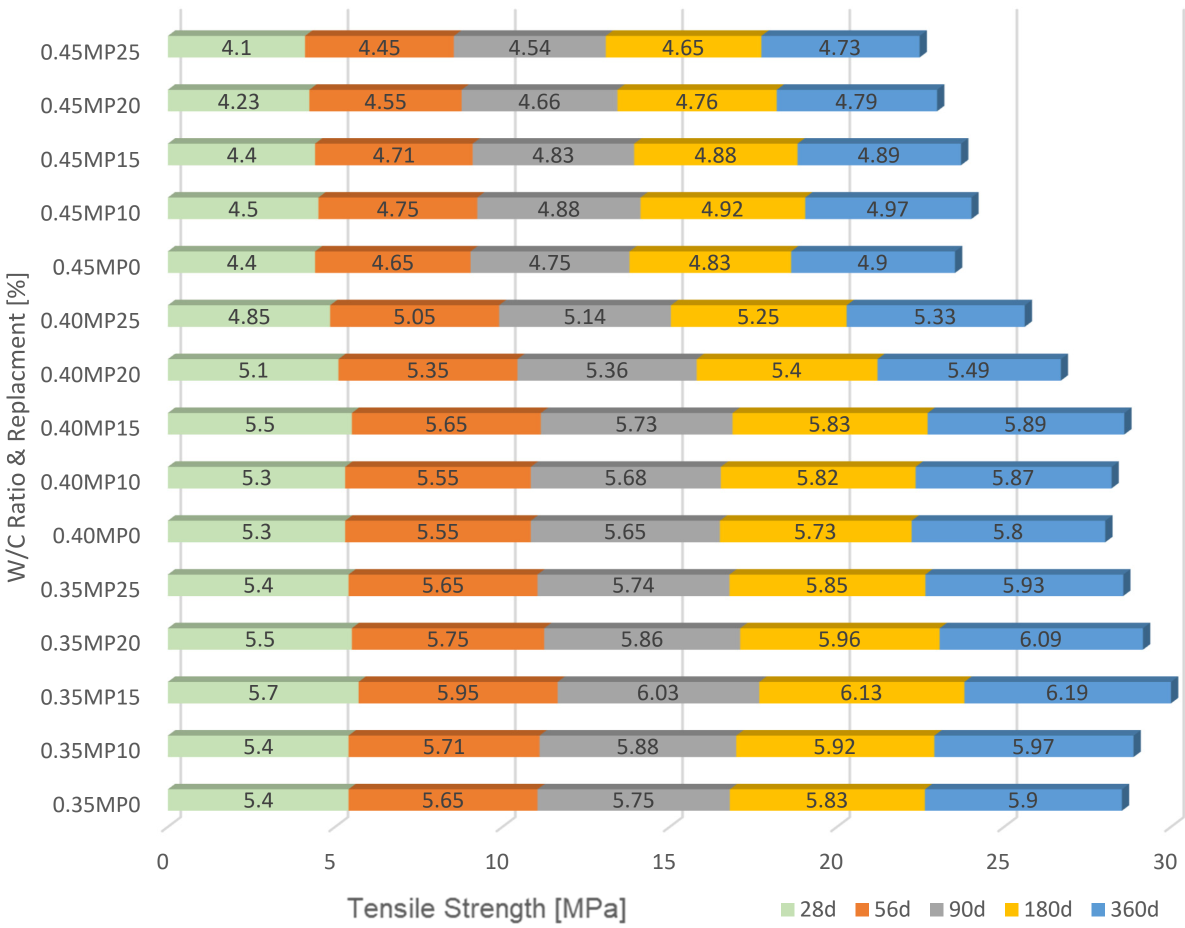

Figure 8. Tensile strength test on different water/cement ratios and MP replacements [%] [98].

Table 9. W/C ratio and MP replacement [%] data for the tensile strength tests shown in Figure 8.

Mix	28 d	56 d	90 d	180 d	360 d
0.35MP0	5.4	5.65	5.75	5.83	5.9
0.35MP10	5.4	5.71	5.88	5.92	5.97
0.35MP15	5.7	5.95	6.03	6.13	6.19
0.35MP20	5.5	5.75	5.86	5.96	6.09
0.35MP25	5.4	5.65	5.74	5.85	5.93
0.40MP0	5.3	5.55	5.65	5.73	5.8
0.40MP10	5.3	5.55	5.68	5.82	5.87
0.40MP15	5.5	5.65	5.73	5.83	5.89
0.40MP20	5.1	5.35	5.36	5.4	5.49
0.40MP25	4.85	5.05	5.14	5.25	5.33
0.45MP0	4.4	4.65	4.75	4.83	4.9
0.45MP10	4.5	4.75	4.88	4.92	4.97
0.45MP15	4.4	4.71	4.83	4.88	4.89
0.45MP20	4.23	4.55	4.66	4.76	4.79
0.45MP25	4.1	4.45	4.54	4.65	4.73

5. Conclusions

From the review of this study, the following can be concluded:

1. Recent studies have confirmed that replacing cement with marble powder up to 10–15% can improve the concrete's mechanical properties, particularly the properties of compressive and tensile strength. This improvement is ascribed to the finer particle size of marble powder, which fills voids in the concrete matrix, reduces porosity, and enhances particle bonding. However, recent research has also highlighted that the performance of marble powder concrete under non-standard conditions, such as under high temperatures or in aggressive chemical environments, requires further investigation. For instance, studies have shown that marble powder can improve the durability of concrete in sulfate-rich environments, but its performance under freeze–thaw cycles remains underexplored.
2. Beyond 15% replacement, there is a substantial reduction in compressive strength, with some studies reporting a loss of up to 26.1% at a 25% replacement level. This decline is due to the dilution of cementitious materials, which reduces the formation of hydration products. Recent research has also explored the impact of marble powder on the long-term durability of concrete, particularly under aggressive environmental conditions. For example, some studies suggest that marble powder can enhance resistance to chemical attacks, but its performance under elevated temperatures or in marine environments remains inconsistent. These findings underscore the need for further research to optimize marble powder content for different environmental conditions.
3. Marble powder can enhance workability up to a moderate replacement level of about 10–15%. However, the workability of concrete is influenced by the particle size distribution and the shape of the marble powder. Finer particles with irregular shapes tend to increase the water demand due to their larger surface area, which can lead to a decline in workability. Therefore, optimizing the particle size and shape of the marble powder is crucial for achieving a balance between workability and strength in concrete mixes. Future research should focus on understanding the relationship between particle characteristics and workability to develop more effective mix designs.

Despite the extensive research on marble powder as a cement replacement, several aspects remain underexplored. These include its long-term performance under varying environmental conditions, such as freeze–thaw cycles, marine exposure, and elevated temperatures. Furthermore, the interaction between marble powder and other supplementary materials, such as fly ash or nano-silica, merits further investigation. Future research should focus on comparing the performance and mechanisms of marble powder in concrete with those of other types of rock powders, optimizing mix designs for enhanced durability and sustainability, while addressing challenges for large-scale implementation, such as consistency in waste marble powder characteristics.

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