

Assessment of calcined marble waste utilization as an eco-efficient aggregate in concrete production

Yasir Nussrat Shukur¹ , Wael R. Abdellah^{2,3*} , Moatasem Mostafa Khalefa⁴ ,
Salah A. Bader⁵ , Mahrous A.M. Ali⁴ 

¹ Petroleum Geology and Minerals Department, College of Science, University of Diyala, Baqubah, Iraq

² Geology Department, College of Science, Taibah University, Al-Madinah, Saudi Arabia

³ Mining and Metallurgical Engineering Department, Assiut University, Assiut, Egypt

⁴ Mining, Metallurgy and Petroleum Engineering Department, Faculty of Engineering, Al-Azhar University, Qena, Egypt

⁵ Mining and Petroleum Engineering Department, Faculty of Engineering-Cairo, Al-Azhar University, Cairo, Egypt

*Corresponding author: e-mail wabdellah@taibahu.edu.sa

Abstract

Purpose. This study investigates the feasibility of using calcined marble cutting residues as a partial substitute for fine aggregates in concrete to improve material sustainability while maintaining mechanical performance. The research aims to evaluate the effects of incorporating marble waste on strength properties and to determine an optimal substitution ratio suitable for practical applications.

Methods. Marble cutting residues were collected, dried, and calcined at 750°C, then ground into a fine powder. The processed material was used to replace natural sand at substitution levels of 0, 5, 10, and 15% by weight. Standard concrete specimens were prepared and cured for 7, 14, and 28 days. Compressive, flexural, and splitting tensile strength tests were conducted in accordance with relevant standards. Microstructural observations were performed to analyze particle distribution, interfacial bonding, and pore structure.

Findings. The results indicate that concrete containing 5% calcined marble waste achieved a 28-day compressive strength of 38.6 MPa, compared with 39.2 MPa for the control mixture. Flexural and tensile strengths at this replacement level varied by less than 4%. In contrast, higher replacement ratios of 10 and 15% reduced strength by up to 12%, primarily due to increased porosity and reduced packing efficiency.

Originality. This study provides systematic experimental evidence on the mechanical and microstructural behavior of concrete containing thermally treated marble residues.

Practical implications. The findings confirm that limited substitution of natural sand with calcined marble waste can be safely used in concrete production, supporting waste valorization, resource conservation, and environmentally sustainable construction practices.

Keywords: calcined marble waste; marble powder; alternative aggregate; sustainable concrete; compressive strength; construction materials

1. Introduction

The global construction sector has experienced unprecedented growth over the past decades, driven by rapid urbanization and infrastructure expansion. This surge has substantially increased demand for concrete, the most widely used engineered composite material worldwide. Consequently, the consumption of natural aggregates, particularly fine aggregates such as sand, has intensified, leading to the depletion of natural resources and environmental degradation associated with their extraction and transport [1], [2]. Simultaneously, ornamental stone processing, particularly marble processing, generates significant amounts of solid waste in the form of powder and slurry from cutting, grinding, and polishing operations. Improper disposal of these

by-products poses environmental challenges, including air, water, and soil pollution [3]-[5].

In response to sustainability concerns, the construction industry has increasingly focused on valorizing industrial by-products as partial substitutes for conventional concrete constituents. Marble waste powder (MWP), obtained from stone processing, has attracted considerable attention for its potential to replace both cement and fine aggregates [6]-[11]. Several studies have shown that incorporating MWP into concrete can maintain or even enhance mechanical properties, such as compressive and tensile strength, while promoting environmental sustainability by reducing natural resource consumption and associated CO₂ emissions [12]-[15]. For instance, Ali et al. [1] reported that marble dust

Received: 11 January 2026. Accepted: 13 April 2026. Available online: 30 June 2026

© 2026. Y.N. Shukur, W.R. Abdellah, M.M. Khalefa, S.A. Bader, M.A.M. Ali
Mining of Mineral Deposits. ISSN 2415-3443 (Online) | ISSN 2415-3435 (Print)

This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted reuse, distribution, and reproduction in any medium, provided the original work is properly cited.

can be effectively used as both a cement and a sand substitute without compromising compressive strength at optimized substitution levels. Similarly, research on high-performance and self-compacting concretes (HPC and SCC) has shown that MWP can improve workability, rheological behavior, and durability while maintaining competitive mechanical performance [16]-[18].

Experimental studies show that the replacement ratio, particle size, and mixture design strongly influence the performance of concrete containing marble waste. Partial substitution of fine aggregate with MWP generally improves particle packing, reducing voids and increasing matrix density [19]. Furthermore, when used as a cement replacement, MWP contributes calcium carbonate to the matrix, which can participate in hydration reactions and potentially refine the microstructure [20], [21]. Studies also suggest that combining MWP with supplementary cementitious materials, such as fly ash or rice husk ash, can further enhance mechanical performance while providing additional sustainability benefits [22].

Despite these promising results, most investigations have focused on uncalcined marble waste. Calcination, which thermally decomposes calcium carbonate (CaCO_3) into calcium oxide (CaO), can alter particle reactivity, increase surface area, and enhance pozzolanic activity. These changes may improve binding reactions, microstructural development, and overall concrete performance [23]. However, the effects of calcined marble waste as a fine aggregate or cement substitute remain largely underexplored. Recent studies have highlighted the potential of calcined or thermally treated industrial waste in concrete applications, suggesting improvements in strength, durability, and environmental performance [24].

Beyond conventional concrete, MWP has also been successfully used in high-performance mortars and SCC, improving workability, reducing segregation, and supporting long-term strength development [25]-[27]. Research on recycled aggregate concrete (RAC) incorporating marble waste shows that partially replacing natural sand or fine aggregate with MWP can maintain compressive strength and durability, underscoring the versatility of marble powder in eco-efficient concrete production [28]-[31]. Life cycle assessment studies further confirm the environmental advantages of replacing natural aggregates with marble by-products, including reductions in water consumption, energy use, and CO_2 emissions [32].

The growing body of research underscores that MWP can serve as a sustainable material in concrete production, supporting resource conservation and contributing to low-carbon construction practices [8]. Nevertheless, the specific impact of calcination on marble dust properties and on subsequent concrete performance remains a critical knowledge gap. Addressing this gap is essential to optimizing the use of marble processing waste in both conventional and high-performance concrete, enabling higher-value reuse of industrial by-products while minimizing environmental impact.

Therefore, this study investigates the use of calcined marble cutting waste powder as a partial substitute for fine aggregates in concrete mixtures at replacement levels of 5, 10, 15, 20, and 25%. The mechanical properties, particularly compressive strength, were evaluated to assess the influence of calcination on concrete performance and to identify optimal substitution levels for eco-efficient and sustainable construction applications [33], [34].

2. Methods

2.1. Materials characterization

Ordinary Portland Cement (OPC) conforming to EN 197-1:2011 served as the primary binder. Natural river sand from the Seyhan River in Adana, Turkey, served as the fine aggregate. The sand was washed, oven-dried, and sieved to remove impurities. Its gradation, physical properties, and cleanliness were verified in accordance with ASTM C33/C33M-18 and TS 706 EN 12620. Coarse aggregate was sourced from a local quarry, with particle sizes ranging from 4.75 to 19 mm, suitable for structural concrete applications.

Marble cutting waste powder (MWP) was obtained from a local processing facility. The waste was oven-dried and sieved through a 75 μm mesh to ensure uniform particle size for use as a fine aggregate replacement. X-ray fluorescence (XRF) analysis was conducted to determine its chemical composition and assess potential reactivity. To enhance pozzolanic activity, the powder was calcined at 800°C for one hour in a controlled electric furnace. The calcined material was gradually cooled to ambient temperature and stored in airtight containers to prevent moisture absorption, ensuring stability, homogeneity, and reactivity for concrete production.

2.2. Concrete mix design

Concrete mixtures were proportioned to evaluate the effect of partially replacing fine aggregate with calcined marble powder (CMP) at 0, 5, 10, 15, 20, and 25% by weight. All mixes were designed to achieve a target compressive strength of 30 MPa at 28 days in accordance with ACI 211.1. A constant water-to-cement ratio of 0.50 was used to isolate the influence of CMP, and a superplasticizer was added as needed to maintain comparable workability across mixtures. All constituents were precisely weighed, and aggregate and cementitious contents were systematically adjusted to accommodate the marble powder substitution, ensuring consistency and comparability across all mix compositions.

2.3. Mixing and casting

Concrete preparation was performed using a mechanical pan mixer to ensure uniform dispersion of all constituents. Initially, coarse and fine aggregates were blended for 2 minutes, followed by the addition of cement and calcined marble powder, with an additional 2 minutes of dry mixing. Water and superplasticizer were then gradually introduced, and mixing continued for 3-4 minutes until a homogeneous, workable consistency was achieved. The fresh concrete was placed into molds for mechanical testing, including 100 × 100 × 100 mm cubes for compressive-strength testing and 100 × 200 mm cylinders for other tests. Placement was carried out in three layers, each compacted with a standard tamping rod to remove entrapped air. A control mix was prepared using the reference proportions in Table 1, after which fine aggregate was progressively replaced with CMP at the specified levels. After casting, all specimens were maintained at 25°C for 48 hours to allow initial hardening before further curing and testing.

2.4. Curing

After casting, specimens were covered with plastic sheets to prevent moisture loss and left at ambient temperature for 24 hours. After demolding, all specimens were submerged in a water-curing tank at $2 \pm 2^\circ\text{C}$ until testing on days 7, 14, and 28. Curing conditions were carefully monitored to ensure consistent hydration and uniform development of mechanical properties.

Table 1. Proportions of the reference concrete mix and mixtures incorporating calcined marble powder as a partial replacement of fine aggregate

Mix ID	Cement, kg/m ³	Fine aggregate, kg/m ³	Marble powder, kg/m ³	Calcined marble powder, kg/m ³	Coarse aggregate, kg/m ³	Water, kg/m ³	W/C ratio
Control	400	750	0	0	1050	200	0.50
M5	400	712.5	37.5	0	1050	200	0.50
M10	400	675	75	0	1050	200	0.50
M15	400	637.5	112.5	0	1050	200	0.50
M20	400	600	150	0	1050	200	0.50
M25	400	562.5	187.5	0	1050	200	0.50
Control	400	750	0	0	1050	200	0.50
cM5	400	712.5	0	37.5	1050	200	0.50
cM10	400	675	0	75	1050	200	0.50
cM15	400	637.5	0	112.5	1050	200	0.50
cM20	400	600	0	150	1050	200	0.50
cM25	400	562.5	0	187.5	1050	200	0.50

2.5. Testing procedures

The mechanical, physical, and microstructural properties of the prepared concrete specimens were evaluated using standardized testing procedures. Compressive strength was determined on cubic specimens after curing periods of 7, 14, and 28 days. Before testing, all specimens were removed from the curing tank, surface-dried, and tested on a calibrated hydraulic compression testing machine in accordance with ASTM C39. The load was applied continuously at a controlled rate until failure, and the maximum load was recorded to calculate the compressive strength.

The workability of fresh concrete mixtures was assessed immediately after mixing using the slump test in accordance with ASTM C143. This test was conducted to evaluate the flow characteristics and consistency of the concrete and to examine the influence of calcined marble powder on fresh-state properties. The slump value was measured as the vertical difference between the slump cone height and the displaced concrete height after mold removal. The density and water absorption of hardened concrete were measured on specimens cured for 28 days. After curing, the samples were oven-dried to a constant mass and then immersed in water for a specified time. The saturated and dry weights were recorded to calculate bulk density and water absorption. These parameters were used to assess the effect of marble powder replacement on the internal structure and porosity of the concrete matrix.

For microstructural characterization, selected specimens were collected after 28 days of curing and prepared for scanning electron microscopy (SEM) and X-ray diffraction (XRD) analyses. SEM observations were conducted to examine the morphology of hydration products and the interfacial transition zone. At the same time, XRD analysis was employed to identify crystalline phases and assess the influence of calcined marble powder on cement hydration. These techniques provided insight into the interaction between the supplementary material and the cementitious matrix, as well as the supplementary material's contribution to the observed macroscopic properties.

3. Results

The marble residue used in this study, hereafter referred to as marble powder (MP), was collected from a local marble processing facility. Before use, the material was oven-dried to remove residual moisture and then sieved through a 75 μm mesh to achieve a uniform fineness suitable for use as a supplementary constituent in concrete.

3.1. Chemical and physical analysis

The elemental oxide composition of ordinary Portland cement, uncalcined MP, and calcined marble powder (CMP) was quantified by X-ray fluorescence (XRF) analysis, and the principal results are summarized in Table 2.

Table 2. Major oxide composition (%) of ordinary Portland cement, marble powder (MP), and calcined marble powder (CMP)

Oxide	Cement	MP	CMP
CaO	64.1	54.38	54.35
CaCO ₃	–	94	95
SiO ₂	19.5	0.5	0.4
Al ₂ O ₃	5.4	0.4	0.3
Fe ₂ O ₃	4.1	0.3	0.2
MgO	1.4	0.7	0.9
SO ₃	2.1	–	–

The results indicate that both MP and CMP are dominated by calcium-based compounds, reflecting their limestone origin. In contrast, Portland cement contains significantly higher proportions of silica, alumina, and iron oxides, which are responsible for its hydraulic and strength-gaining characteristics. The very low levels of siliceous and aluminous phases in the marble-derived powders suggest minimal natural pozzolanic activity when used without modification.

Figure 1 shows an X-ray diffraction (XRD) pattern of the analyzed sample, plotted as intensity versus 2θ , revealing several crystalline phases. The most intense and sharp diffraction peaks are assigned to dolomite (D), indicating that it is the dominant mineral phase in the sample. Additional peaks corresponding to calcite (C) and calcium carbonate (CaCO₃) confirm the coexistence of secondary carbonate phases, which may result from partial dolomitization or phase mixing. Minor peaks attributed to silicon carbide (S) suggest either trace contamination or the presence of an intentionally added component related to processing or material reinforcement. The overall sharpness of the main reflections indicates good crystallinity, whereas the elevated background at lower diffraction angles may indicate the presence of fine-grained or partially amorphous material.

To enhance the reactivity of the marble waste, the sieved MP was thermally treated in an electrically controlled furnace at 800°C for 60 minutes. This process aimed to convert calcium carbonate to a more reactive calcium oxide phase via decarbonation, thereby enabling secondary reactions within cementitious matrices.

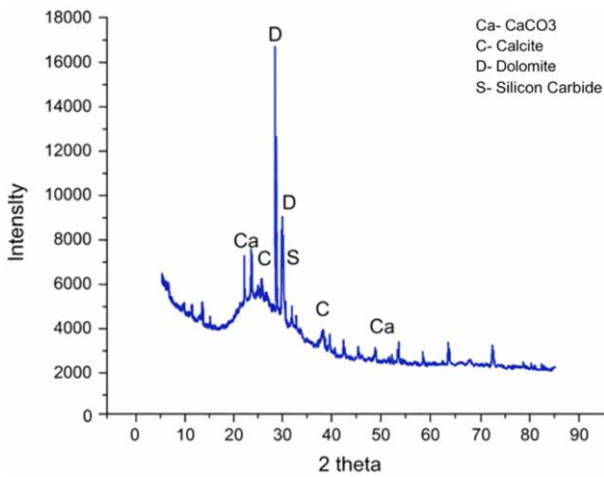


Figure 1. X-ray diffraction (XRD) pattern of the investigated sample showing a dominant dolomite (D) phase with secondary calcite (C), calcium carbonate (CaCO₃), and minor silicon carbide (S) phases

After heating, the calcined material was allowed to cool gradually to ambient temperature and then stored in airtight containers to prevent premature carbonation or moisture uptake. This handling procedure ensured consistency and preserved the chemical state of CMP before mixing and testing.

The main physical properties of MP and CMP are presented in Table 3.

Table 3. Physical properties of uncalcined (MP) and calcined marble powder (CMP)

Property	MP	CMP
Density, g/cm ³	2.75-2.90	2.60-2.75
Water absorption, %	0.4-0.6	0.5-0.8
Color and appearance	White to cream, smooth surface	Pale yellowish white, more porous
Particle size, μm	55-100	50-90

Thermal treatment led to a moderate decrease in density and a noticeable increase in water absorption, attributed to the formation of internal pores from the release of carbon dioxide during calcination. Additionally, CMP exhibited a slightly narrower particle-size distribution and a more open texture, features that may improve particle packing and provide a beneficial filler effect when incorporated into cement-based composites.

Overall, the observed chemical and physical changes are consistent with prior studies of heat-treated calcareous by-products, in which controlled calcination enhances surface characteristics and reactivity while maintaining material stability. Based on these characteristics, both MP and CMP were considered suitable candidates for subsequent evaluation as partial substitutes for cement or aggregates in environmentally sustainable concrete systems.

3.2. Mechanical characteristics before calcination

The mechanical performance of concrete and cement-stabilized materials can be evaluated using complementary tests, including unconfined compressive strength (UCS), point load strength, ultrasonic pulse velocity (UPV), and surface hardness. UCS reflects the material’s overall load-bearing capacity; point load strength assesses resistance to localized or tensile stresses; UPV indicates internal compactness and micro-structural continuity; and surface hardness evaluates resistance to indentation, which correlates with resistance to abrasion or

impact. Collectively, these tests provide a comprehensive understanding of structural and durability-related properties and allow evaluation of the effects of mineral additives, such as marble powder, before and after thermal activation.

3.2.1. Effect of marble powder on early-age and 28-day strength

Figure 2 shows the development of unconfined compressive strength (UCS) of the cement-stabilized material before calcination as a function of marble powder content and curing duration. The grouped bars indicate that strength consistently increases with curing time across all mixtures, reflecting the ongoing progression of cement hydration. During the early curing stages (3-14 days), UCS values remain relatively low and are relatively insensitive to changes in marble powder dosage. In contrast, at later ages, particularly after 28 and 56 days, clear differences emerge among the mixtures.

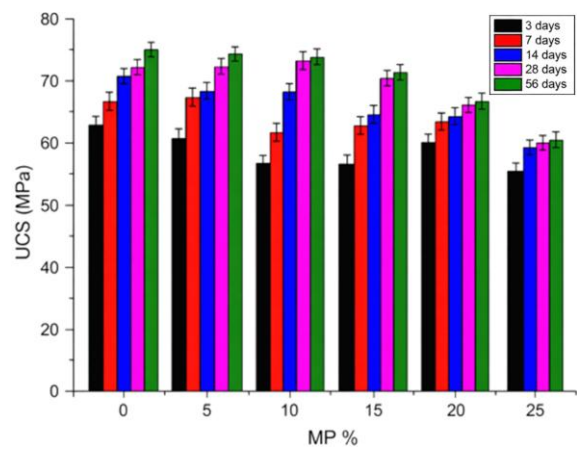


Figure 2. Effect of initial mixing moisture content and curing period on the unconfined compressive strength of the cement-stabilized material prior to calcination

The reference mix without marble powder attains the highest UCS, approaching 40 MPa, whereas increasing levels of marble powder gradually reduce strength. This reduction becomes more pronounced when the replacement level exceeds approximately 15-20%, leading to notably lower UCS values at the highest dosage. Although some scatter is evident in the data, the overall trend indicates that excessive incorporation of marble powder adversely affects long-term compressive strength, likely due to a reduced proportion of reactive cementitious phases and modifications in the internal structure. These observations align with trends commonly reported in related studies on cement-stabilized systems incorporating mineral powder additives.

3.2.2. Point load strength of concrete with marble powder

Figure 3 illustrates how the point load strength of the cement-stabilized material before calcination varies with marble powder content and curing age. The results show a consistent increase in load-bearing capacity with longer curing for all mixtures, reflecting the gradual development of cementitious bonding. Specimens with little to no marble powder show the highest resistance to concentrated loading, and the longest curing period yields peak values near the upper end of the measurement range. As the proportion of marble powder increases, point load strength decreases, with the decline becoming particularly pronounced at replacement levels beyond 20%, especially after prolonged curing.

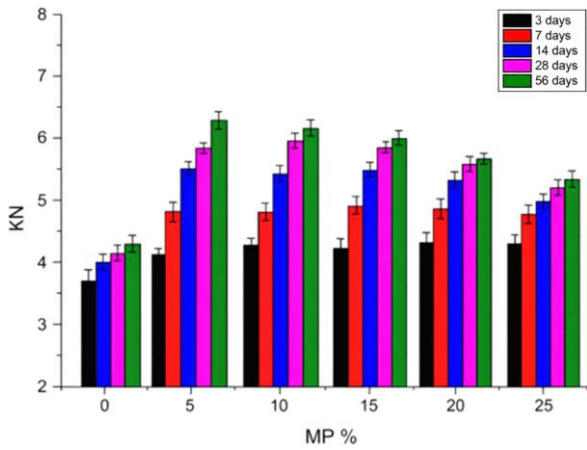


Figure 3. Effect of marble powder content and curing age on the point load strength of cement-stabilized material before calcination

At early ages, differences among mixtures are relatively minor, and overall strength remains limited due to incomplete hydration. Although some variability is evident in the test results, the overall trend indicates that excessive incorporation of marble powder weakens the material’s resistance to localized loading, likely due to reduced formation of binding phases and a less cohesive internal structure.

These findings emphasize the need to control the dosage of marble powder to preserve adequate tensile and toughness characteristics in cement-stabilized systems before calcination.

3.2.3. Ultrasonic pulse velocity of concrete with marble powder

Figure 4 shows how varying marble powder (MP) content affects the ultrasonic pulse velocity (UPV) of concrete after 56 days of curing. At low MP replacement levels (0-15%), UPV remains relatively stable, around 4.20 km/s, indicating that small additions of MP do not significantly affect the concrete’s internal compactness or integrity. However, when the replacement exceeds 15%, UPV declines noticeably, dropping sharply to approximately 4.11 km/s at 25% MP.

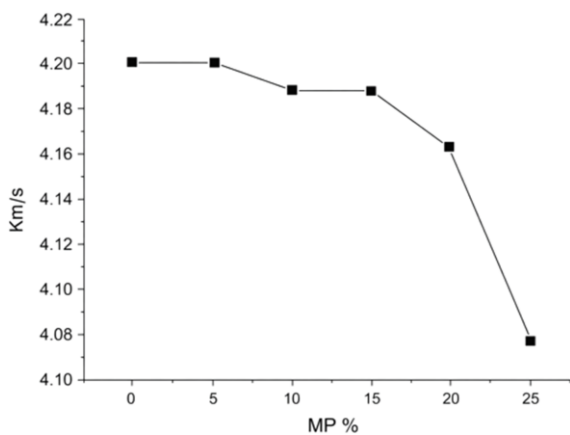


Figure 4. Effect of marble powder (MP) content on the ultrasonic pulse velocity (UPV) of concrete after 56 days of curing

This trend indicates that higher marble powder content may create microstructural discontinuities, increase porosity, and reduce density, all of which adversely affect the propagation of ultrasonic waves. Overall, the figure demonstrates that moderate incorporation of marble powder maintains concrete quality, whereas excessive amounts compromise its homogeneity and internal structure.

3.2.4. Surface hardness of concrete incorporating granite powder

Figure 5 shows the surface hardness of concrete mixtures in which marble powder (GP) partially replaces cement, measured after 56 days of curing.

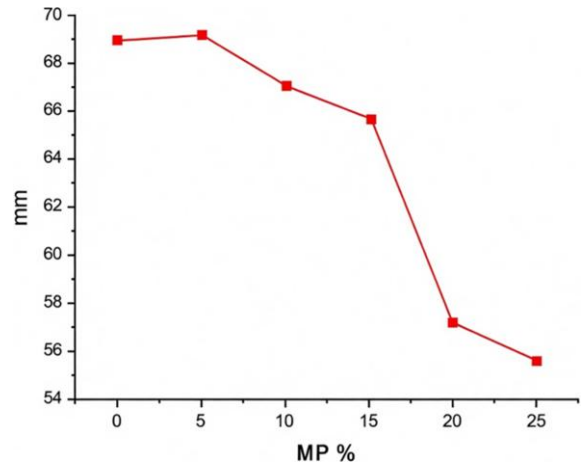


Figure 5. Effect of marble powder content on concrete surface hardness after 56 days of curing

It plots GP replacement levels (0-25%) on the x-axis and hardness measurements (in mm, likely reflecting penetration depth from a rebound or sclerometer test, where higher values indicate softer surfaces) on the y-axis, ranging roughly from 54 to 70 mm. The red line connecting the data points shows that penetration gradually increases as the proportion of GP rises. Starting around 68 mm at 0% GP, the values remain constant up to 10%, then increase more sharply beyond 15%, reaching approximately 70 mm at 25% GP.

This trend indicates that higher GP content progressively reduces surface hardness, which may be attributed to reduced formation of dense hydration products, increased microvoid formation, or the softening effect of inert GP particles within the cement matrix.

The results suggest that small amounts of marble powder have minimal effect on surface strength, whereas higher replacement levels can reduce the concrete’s resistance to indentation. Therefore, careful limitation of GP content is advised to preserve hardness and durability in eco-friendly concrete mixes. Similar studies using marble, granite, or other recycled powder replacements report comparable decreases in mechanical properties, including surface hardness, with increasing levels of cement substitution after extended curing periods.

3.3. Mechanical properties after calcination

3.3.1. Effect of calcined marble powder on early-age and 28-day strength

Figure 6 shows the development of unconfined compressive strength (UCS) of concrete containing 0-25% calcined marble powder (CMP) as a partial cement replacement, measured at 3, 7, 14, 28, and 56 days. Strength increases consistently with curing time across all mixtures, with the greatest gains occurring between 7 and 28 days. Mixtures with up to 15% CMP achieve UCS comparable to or slightly higher than the control, reaching nearly 42 MPa at 56 days for 5-15% replacement. Beyond 15%, strength gradually declines, with 20 and 25% CMP showing noticeable reductions at longer curing ages, though still improving over time.

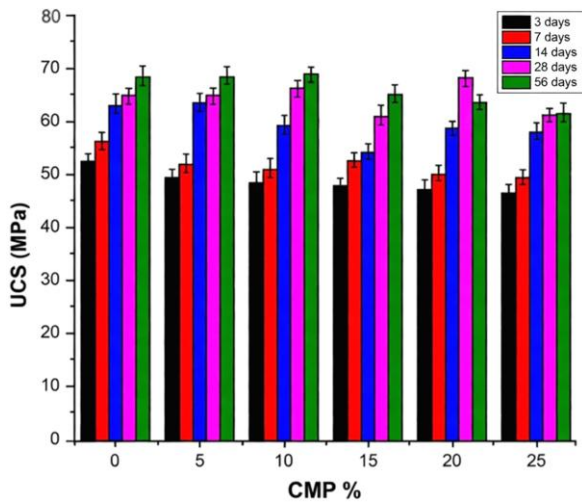


Figure 6. Development of uniaxial compressive strength of concrete containing 0-25% calcined marble powder at 3, 7, 14, 28, and 56 days

The results indicate that moderate CMP addition can enhance or sustain compressive performance through secondary hydration reactions, whereas excessive substitution dilutes the cement matrix and limits long-term strength. These findings align with studies on calcined clay, metakaolin, and other thermally treated waste powders, which often show optimal compressive performance at 10-20% replacement, followed by declines at higher dosages.

3.3.2. Point load strength of concrete with calcined marble powder

Figure 7 presents the point-load strength of concrete mixtures containing 0-25% calcined marble powder (CMP) as a partial cement replacement, measured at 3, 7, 14, 28, and 56 days. Strength increases steadily with curing across all mixtures due to ongoing primary and secondary hydration. Mixtures with 5-15% CMP achieve the highest performance, often matching or exceeding the control, with 56-day values peaking near 8 kN at 5-10% replacement. Higher CMP levels (20-25%) show noticeable declines, particularly at later ages, while early-age differences (3-14 days) are minor. These results indicate that moderate CMP improves tensile-related properties by refining the microstructure, whereas excessive substitution dilutes the binder and weakens interfacial zones.

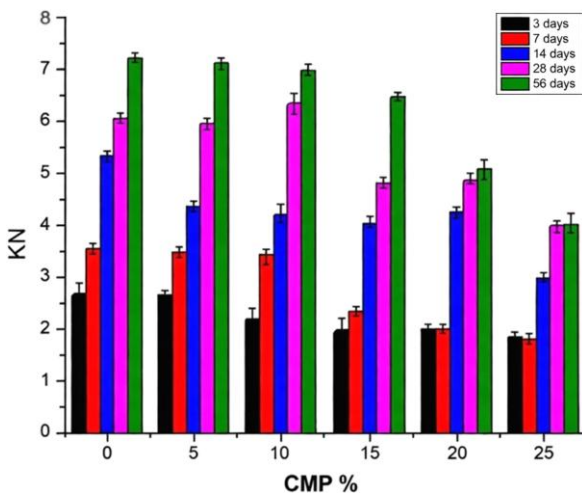


Figure 7. Effect of calcined marble powder content on the point load strength of concrete over 3-56 days

Comparable studies on calcined clays, marble dust, and other pozzolanic additives show similar trends, with enhanced strength at moderate replacement levels and reductions at higher dosages across curing periods.

3.3.3. Ultrasonic pulse velocity of concrete with marble powder

Figure 8 illustrates the ultrasonic pulse velocity (UPV) of concrete containing 0-25% calcined marble powder (CMP) after 56 days of curing. The line graph plots CMP content on the x-axis and UPV (km/s) on the y-axis, with values ranging from roughly 4.0 to 5.0 km/s. Pulse velocity increases slightly from 4.2 km/s in the control to a peak of 4.8-4.9 km/s at 5-10% CMP, then gradually declines, remains stable up to 15-20%, and drops to near 4.2 km/s at 25% replacement.

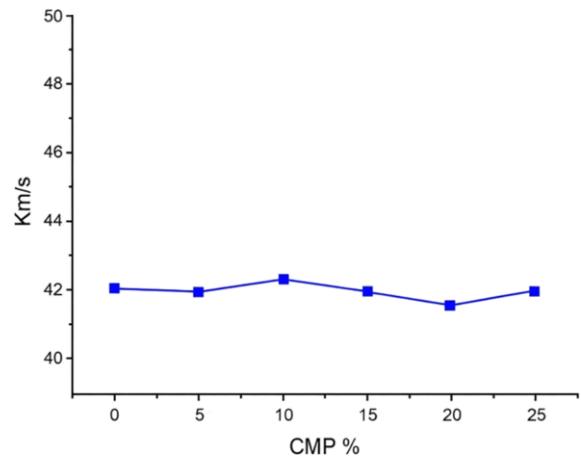


Figure 8. Ultrasonic pulse velocity of concrete containing 0-25% calcined marble powder after 56 days

This trend suggests that moderate CMP additions enhance concrete density and microstructural continuity via pozzolanic activity, improving wave propagation and internal homogeneity. In contrast, higher dosages introduce excess inert material, increasing porosity and weakening the matrix. The results indicate an optimal CMP replacement range of 5-15% for superior UPV, which correlates with improved durability and reduced permeability. Similar patterns are observed in studies using calcined clays, metakaolin, and thermally treated marble or granite powders, where moderate substitution enhances UPV and higher levels reduce it after extended curing.

3.3.4. Surface hardness of concrete incorporating calcined marble powder

Figure 9 shows the surface hardness of concrete containing 0-25% calcined marble powder (CMP) after 56 days, measured by penetration depth (mm), with higher values indicating softer surfaces. Penetration depth increases slightly from ~69 mm in the control to 70-71 mm at 5-10% CMP, then decreases steadily beyond 15%, reaching ~66 mm at 25% replacement. This trend suggests that low-to-moderate CMP slightly softens the surface, possibly due to early microstructural changes. In contrast, higher CMP levels enhance pozzolanic activity and secondary C-S-H formation, producing a denser surface and improved indentation resistance. Overall, these results indicate that elevated CMP dosages (20-25%) can optimize surface hardness, thereby supporting durability improvements in sustainable concrete mixes, including abrasion and impact resistance.

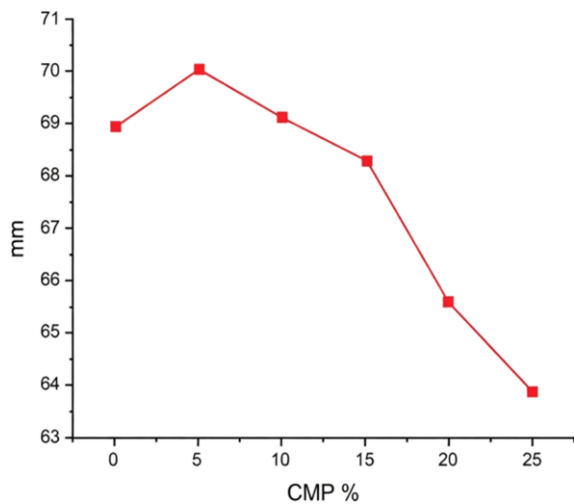


Figure 9. Surface hardness of concrete containing 0-25% calcined marble powder after 56 days

Similar studies on marble dust, calcined powders, and other supplementary cementitious materials report comparable trends: moderate to high replacement levels enhance surface properties after extended curing.

4. Discussions

Figures 2-5 illustrate the influence of raw marble powder (MP) or granite powder (GP) on concrete properties before calcination. UCS and point-load strength increase steadily with curing time, reflecting progressive hydration, but their sensitivity to marble powder content becomes evident at later ages. Specifically, UCS decreases gradually as MP content rises, with significant reductions beyond 15-20% replacement (Fig. 2), indicating that excessive inert powder dilutes reactive cementitious phases and weakens the internal structure. A similar trend is observed for point-load strength (Fig. 3), where higher MP content reduces resistance to localized loading, particularly after prolonged curing. UPV measurements (Fig. 4) remain largely stable up to 15% MP but drop sharply at 25%, suggesting that high powder content introduces microstructural discontinuities, increases porosity, and reduces density. Surface hardness (Fig. 5) also declines progressively with increasing GP content, especially beyond 15%, reflecting softer surfaces due to reduced formation of dense hydration products and the inert filler effect. Collectively, these findings indicate that while low levels of raw marble powder have minimal impact, higher replacement levels compromise both structural and durability-related properties.

Figures 6-9 highlight the effects of calcined marble powder (CMP) on the same properties after thermal activation. UCS shows notable improvement at replacement levels up to 15%, with 5-15% CMP yielding values comparable to or slightly exceeding the control, reaching approximately 42 MPa at 56 days (Fig. 6). Beyond 15% CMP, strength gradually declines but continues to improve over time due to ongoing hydration. Point load strength exhibits a similar pattern (Fig. 7), with optimal performance at 5-15% CMP and noticeable reductions at 20-25%. UPV results (Fig. 8) show that moderate CMP additions (5-15%) increase pulse velocity from ~4.2 km/s to 4.8-4.9 km/s, indicating improved microstructural density and homogeneity, while excessive CMP slightly reduces velocity due to increased inert content. Surface hardness (Fig.9) shows that low to moderate CMP

(5-10%) initially softens the surface, whereas higher replacement levels (15-25%) enhance hardness, likely due to pozzolanic refinement and secondary C-S-H formation. These improvements collectively suggest that calcination activates the marble powder, increasing its pozzolanic reactivity, refining the microstructure, and enhancing both mechanical and durability-related characteristics at moderate replacement levels.

Comparing the results before (Figs. 2-5) and after calcination (Figs. 6-9) reveals several key insights.

Calcination of marble powder markedly alters its behavior in cementitious composites, converting an otherwise inert filler into a reactive supplementary cementitious material (SCM) and extending the optimal replacement range while enhancing compressive, tensile-related, and durability-related properties. Compressive strength tests show that raw marble progressively reduces UCS beyond 15% replacement, whereas calcined marble powder (CMP) achieves UCS values equal to or exceeding the control at 5-15% replacement, reflecting increased reactivity and additional C-S-H formation that densifies the cement matrix. Point load strength measurements similarly indicate that CMP improves tensile-related properties at moderate dosages by strengthening interfacial cohesion, whereas raw marble reduces performance at higher levels. Microstructural evaluation via UPV confirms these trends, with notable densification at 5-15% CMP replacement. In comparison, raw marble shows limited improvement up to 15% and then declines, underscoring the role of thermal activation in enhancing filler reactivity and structural continuity. Surface hardness exhibits a distinct pattern: raw marble progressively reduces hardness at higher dosages, whereas CMP initially softens the surface at very low replacement (5-10%) but enhances hardness at 15-25%, demonstrating pozzolanic refinement of the surface microstructure that improves resistance to indentation, abrasion, and impact. These results align with the literature on thermally activated SCMs, including calcined clays and metakaolin, where moderate substitution enhances mechanical performance and durability. In contrast, higher dosages maintain acceptable properties, whereas untreated powders primarily act as inert fillers. For example, calcined Algerian clay activated at ~700°C increased compressive and flexural strengths by ~15-20% with ~20% replacement, through pozzolanic reactivity and matrix densification [35]. Metakaolin exhibits similar improvements in porosity, long-term strength, and microstructural refinement [36], [37], consistent with the mechanisms observed in the present study.

5. Conclusions

This study investigated how calcined marble powder (CMP), derived from marble cutting residues, affects the mechanical and durability properties of concrete. The research compared performance before and after calcination, evaluating unconfined compressive strength (UCS), point load strength, ultrasonic pulse velocity (UPV), and surface hardness across substitution levels of 0-25%. The findings provide clear evidence of the benefits of thermal activation and highlight optimal usage levels for sustainable concrete production.

Before calcination, incorporating raw marble powder (MP) or granite powder (GP) generally reduced mechanical performance at higher replacement levels. UCS and point load strength increased with curing time but were negatively affected

ted at 15-20% powder content, reflecting the diluting effect of the inert material on the cementitious phases. Similarly, UPV measurements and surface hardness tests showed minor changes at low substitution levels but significant declines at 20-25% replacement, suggesting increased porosity, microstructural discontinuities, and softer surfaces. These results underscore that untreated marble residues act primarily as fillers, providing limited improvement in concrete compactness or durability while compromising strength when used excessively.

In contrast, calcined marble powder significantly enhanced mechanical performance at moderate replacement levels (5-15%). Compressive strength for these mixes matched or slightly exceeded that of control specimens, reaching up to 42 MPa at 56 days, while point load strength peaked within this range. UPV data confirmed improved internal homogeneity and density, with pulse velocity increasing from ~4.2 km/s in the control to 4.8-4.9 km/s at 5-10% CMP. Surface hardness also improved at higher CMP dosages, reflecting the pozzolanic activity induced by calcination, which generates secondary C-S-H products and refines the microstructure. These results demonstrate that thermal treatment transforms marble powder from an inert filler into a reactive supplementary cementitious material, enhancing both structural and durability-related properties.

The study further shows that excessive substitution beyond 15% may slightly reduce performance due to dilution of the cement matrix, though even at 20-25% CMP, the concrete still exhibits reasonable mechanical behavior over time. This finding offers practical guidance for mix design, suggesting an optimal CMP replacement range of 5-15% to balance performance, sustainability, and material utilization.

Overall, the work demonstrates the feasibility of valorizing marble-industry by-products as eco-friendly construction materials, reducing reliance on natural aggregates and minimizing environmental burdens from waste disposal. Integrating calcined marble powder into concrete not only maintains or improves mechanical performance but also supports sustainable construction practices. The study supports adopting CMP as a partial replacement for fine aggregate in concrete, offering a cost-effective, environmentally responsible, and technically sound solution for greener infrastructure development.

Author contributions

Conceptualization: YNS; Data curation: YNS, WA; Formal analysis: YNS, WA; Investigation: YNS, WA; Methodology: YNS, MMK; Project administration: SAB, MAMA; Resources: YNS, SAB; Supervision: MAMA; Validation: YNS, SAB; Visualization: MMK, MAMA; Writing – original draft: YNS, WA; Writing – review & editing: WA. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Acknowledgements

The authors gratefully acknowledge the Department of Petroleum, Geology, and Minerals for providing the infrastructure and institutional support essential to the successful execution of this study. Special appreciation is also extended to the technical staff of the Materials and Rock Mechanics Laboratory, whose expertise, dedication, and technical assistance were instrumental in completing all experimental phases.

Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

References

- Ali, S., Ahmad, S., & Ullah, I. (2024). Utilization of waste marble dust as cement and sand replacement in concrete. *Discover Civil Engineering*, 1(1), 15. <https://doi.org/10.1007/s44290-024-00014-w>
- Aruntaş, H.Y., Gürü, M., Dayı, M., & Tekin, I. (2010). Utilization of waste marble dust as an additive in cement production. *Materials & Design*, 31(8), 4039-4042. <https://doi.org/10.1016/j.matdes.2010.03.036>
- Akbulut, H., & Güler, C. (2007). Use of aggregates produced from marble quarry waste in asphalt pavements. *Building and Environment*, 42(5), 1921-1930. <https://doi.org/10.1016/j.buildenv.2006.03.012>
- Acchar, W., Vieira, F.A., & Hotza, D. (2006). Effect of marble and granite sludge in clay materials. *Materials Science and Engineering: A*, 419(1-2), 306-309. <https://doi.org/10.1016/j.msea.2006.01.021>
- Bilgin, N., Yeprem, H.A., Arslan, S.Ö.N.M.E.Z., Bilgin, A., Günay, E., & Marşoğlu, M. (2012). Use of waste marble powder in brick industry. *Construction and Building Materials*, 29, 449-457. <https://doi.org/10.1016/j.conbuildmat.2011.10.011>
- Binici, H., Shah, T., Aksogan, O., & Kaplan, H. (2008). Durability of concrete made with granite and marble as recycle aggregates. *Journal of Materials Processing Technology*, 208(1-3), 299-308. <https://doi.org/10.1016/j.jmatprotec.2007.12.120>
- Saboya Jr.F., Xavier, G.C., & Alexandre, J. (2007). The use of the powder marble by-product to enhance the properties of brick ceramic. *Construction and Building Materials*, 21(10), 1950-1960. <https://doi.org/10.1016/j.conbuildmat.2006.05.029>
- de Jesus, J.O.N., da Silva, L.J., Parente, V., Esquerre, K.P.O., Sahin, O., & de Araujo, W.C. (2025). A water consumption assessment in the production of marble, granite, and quartz-based composites using life cycle assessment: A case study in Bahia, Brazil. *Water*, 17(10), 1438. <https://doi.org/10.3390/w17101438>
- Hamza, R., El-Haggar, S., & Khedr, S. (2011). Utilization of marble and granite waste in concrete bricks. *International Conference on Environment and Bioscience IPCBEE*, 21, 286-291. <https://doi.org/10.7763/IJBBB.2011.V1.54>
- Varela, J.J., Petter, C.O., & Wotruba, H. (2006). Product quality improvement of Brazilian impure marble. *Minerals Engineering*, 19(4), 355-363. <https://doi.org/10.1016/j.mineng.2005.10.009>
- Okagbue, C.O., & Onyeobi, T.U.S. (1999). Potential of marble dust to stabilise red tropical soils for road construction. *Engineering Geology*, 53(3-4), 371-380. [https://doi.org/10.1016/S0013-7952\(99\)00036-8](https://doi.org/10.1016/S0013-7952(99)00036-8)
- Garko, M.N., Dulawat, S., Ahmad, E., Ubayi, S.S., & Ibrahim, I.A. (2020). Examining the use of marble waste as a substitute of conventional materials in concrete: A brief review. *Environmental Research and Technology*, 8(2), 471-486. <https://doi.org/10.35208/ert.1511775>
- Memon, M.J., Jhatial, A.A., Rid, Z.A., Rind, T.A., & Sandhu, A.R. (2019). Marble powder as fine aggregates in concrete. *Engineering, Technology & Applied Science Research*, 9(3), 4105-4107. <https://doi.org/10.48084/etasr.2698>
- Ashish, D.K. (2019). Concrete made with waste marble powder and supplementary cementitious material for sustainable development. *Journal of Cleaner Production*, 211, 716-729. <https://doi.org/10.1016/j.jclepro.2018.11.245>
- Aliabdo, A.A., Abd Elmoaty, M., & Auda, E.M. (2014). Re-use of waste marble dust in the production of cement and concrete. *Construction and Building Materials*, 50, 28-41. <https://doi.org/10.1016/j.conbuildmat.2013.09.005>
- Corinaldesi, V., Moriconi, G., & Naik, T.R. (2010). Characterization of marble powder for its use in mortar and concrete. *Construction and Building Materials*, 24(1), 113-117. <https://doi.org/10.1016/j.conbuildmat.2009.08.013>
- Kore, S.D., & Vyas, A.K. (2016). Impact of marble waste as coarse aggregate on properties of lean cement concrete. *Case Studies in Construction Materials*, 4, 85-92. <https://doi.org/10.1016/j.cscm.2016.01.002>
- Parmar, S., & Das, S.K. (2021). Effect of marble slurry as a partial substitution of ordinary Portland cement in lean concrete mixes. *Structural Concrete*, 22, E514-E527. <https://doi.org/10.1002/suco.202000059>

- [19] Meng, X.C., Li, C., Wang, Z.H., Gong, X.Z., Liu, Y., & Sun, B.X. (2014). A life cycle inventory case study for marble mining in China. *Materials Science Forum*, 787, 171-175. <https://doi.org/10.4028/www.scientific.net/MSF.787.171>
- [20] Kore, S.D., Vyas, A.K., & Kabeer, S.A. (2020). A brief review on sustainable utilisation of marble waste in concrete. *International Journal of Sustainable Engineering*, 13(4), 264-279. <https://doi.org/10.1080/19397038.2019.1703151>
- [21] Gencel, O., Nodehi, M., Bayraktar, O.Y., Kaplan, G., Benli, A., Koksakal, F., & Ozbakkaloglu, T. (2022). The use of waste marble for cleaner production of structural concrete: A comprehensive experimental study. *Construction and Building Materials*, 361, 129612. <https://doi.org/10.1016/j.conbuildmat.2022.129612>
- [22] Khan, K., Ahmad, W., Amin, M.N., Ahmad, A., Nazar, S., Alabdullah, A.A., & Arab, A.M.A. (2022). Exploring the use of waste marble powder in concrete and predicting its strength with different advanced algorithms. *Materials*, 15(12), 4108. <https://doi.org/10.3390/ma15124108>
- [23] El-Sayed, H.A., Farag, A.B., Kandeel, A.M., Younes, A.A., & Yousef, M.M. (2018). Characteristics of the marble processing powder waste at Shaq El-Thoaban industrial area, Egypt, and its suitability for cement manufacture. *HBRC Journal*, 14(2), 171-179. <https://doi.org/10.1016/j.hbrj.2016.06.002>
- [24] Ali, S.R., Jain, A., v Tripathi, S., Khan, A., & Sen, S (2022). Partial replacement of cement by marble dust. *International Journal of Engineering Sciences & Research Technology*, 11(5), 16-20. <https://doi.org/10.5281/ZENODO.6623536>
- [25] Basaran, B., Kalkan, I., Aksoylu, C., Özkılıç, Y.O., & Sabri, M.M.S. (2022). Effects of waste powder, fine and coarse marble aggregates on concrete compressive strength. *Sustainability*, 14(21), 14388. <https://doi.org/10.3390/su142114388>
- [26] Saloni, Parveen, Lim, Y.Y., Pham, T.M., Jatin, & Kumar, J. (2021). Sustainable alkali activated concrete with fly ash and waste marble aggregates: Strength and durability studies. *Construction and Building Materials*, 283, 122795. <https://doi.org/10.1016/j.conbuildmat.2021.122795>
- [27] Sugathan, A. (2016). Investigation on compressive strength of concrete utilizing broken marble tiles as coarse aggregate. *International Journal of Engineering Sciences & Research Technology*, 3(5), 2395-0056.
- [28] Demir, T., & Alyamaç, K.E. (2022). Investigation of the use of marble powder in production of high strength concretes. *Open Journal of Nano*, 7(1), 18-25. <https://doi.org/10.56171/ojn.1034691>
- [29] Alyamaç, K.E., & Aydin, A.B. (2015). Concrete properties containing fine aggregate marble powder. *KSCSE Journal of Civil Engineering*, 19(7), 2208-2216. <https://doi.org/10.1007/s12205-014-0198-5>
- [30] Ghani, A., Ali, Z., Khan, F.A., Shah, S.R., Khan, S.W., & Rashid, M. (2020). Experimental study on the behavior of waste marble powder as partial replacement of sand in concrete. *SN Applied Sciences*, 2, 1554. <https://doi.org/10.1007/s42452-020-03292-9>
- [31] Vigneshpandian, G.V., Shruthi, E.A., Venkatasubramanian, C., & Muthu, D. (2017). Utilisation of waste marble dust as fine aggregate in concrete. *IOP Conference Series: Earth and Environmental Science*, 80, 012007. <https://doi.org/10.1088/1755-1315/80/1/012007>
- [32] Varadharajan, S., Jaiswal, A., & Verma, S. (2020). Assessment of mechanical properties and environmental benefits of using rice husk ash and marble dust in concrete. *Structures*, 28, 389-406. <https://doi.org/10.1016/j.istruc.2020.09.028>
- [33] Meera, M., & Gupta, S. (2024). Performance evaluation of marble powder and fly ash concrete. *Journal of Building Engineering*, 84, 108499. <https://doi.org/10.1016/j.jobee.2024.108499>
- [34] Kirgiz, M.S., Khatib, J., & de Sousa Galdino, A.G. (2025). Waste marble sludge and calcined clay brick powders in conventional cement farina production for cleaner built environment. *Scientific Reports*, 15, 3467. <https://doi.org/10.1038/s41598-024-83163-3>
- [35] Badaoui, M., Hebbache, K., Douadi, A., Mansouri, L., Merdas, A., Gherbi, S., & Szymanowski, J. (2025). Utilization of Algerian calcined clay in sustainable mortars considering thermal treatment and granulometry effects on mechanical properties. *Scientific Reports*, 15(1), 21704. <https://doi.org/10.1038/s41598-025-04342-4>
- [36] Geu, M.J., Zhuge, Y., Ma, X., & Pham, T.M. (2026). Systematic review of physical, mechanical and durability performances of metakaolin concrete. *Applied Clay Science*, 279, 108048. <https://doi.org/10.1016/j.clay.2025.108048>
- [37] Strybny, B., Schack, T., Link, J., & Haist, M. (2024). Calcined clays as concrete additive in structural concrete: workability, mechanical properties, durability, and sustainability performance. *Materials*, 17(18), 4517. <https://doi.org/10.3390/ma17184517>

Оцінка можливості використання кальцинованих відходів мрамру як екоефективного заповнювача у виробництві бетону

Я.Н. Шукур, В.Р. Абделлах, М.М. Халефа, С.А. Бадер, М.А.М. Алі

Мета. У дослідженні розглянуто можливість використання кальцинованих відходів різання мрамру як часткового замітника дрібного заповнювача в бетоні з метою підвищення екологічної ефективності матеріалу за збереження його механічних властивостей. Робота спрямована на оцінювання впливу мрамрових відходів на показники міцності бетону та визначення оптимальної частки заміщення, придатної для практичного застосування.

Методика. Відходи різання мрамру збирали, висушували та піддавали кальцинації при температурі 750°C, після чого подрібнювали до тонкодисперсного стану. Отриманий матеріал використовували для заміщення природного піску в кількості 0, 5, 10 і 15% за масою. Стандартні бетонні зразки виготовляли та витримували протягом 7, 14 і 28 діб. Визначали міцність на стиск, вигин і розтяг при розколюванні відповідно до чинних стандартів. Також проведено мікроструктурні дослідження для аналізу розподілу частинок, міжфазного зчеплення та порової структури.

Результати. Показано, що бетон зі вмістом 5% кальцинованих мрамрових відходів мав міцність на стиск через 28 діб на рівні 38.6 МПа, тоді як для контрольного складу цей показник становив 39.2 МПа. За такого рівня заміщення міцність на вигин і розтяг змінювалася менш ніж на 4%. Водночас підвищення частки заміщення до 10 і 15% зумовлювало зниження міцності до 12%, що насамперед пов'язано зі збільшенням пористості та погіршенням щільності пакування частинок.

Наукова новизна. Робота надає систематизовані експериментальні дані щодо механічної поведінки та мікроструктурних особливостей бетону, що містить термічно оброблені мрамрові відходи.

Практична значимість. Отримані результати підтверджують, що обмежене заміщення природного піску кальцинованими мрамровими відходами може безпечно застосовуватися у виробництві бетону, сприяючи утилізації відходів, збереженню природних ресурсів і впровадженню екологічно сталих підходів у будівництві.

Ключові слова: кальциновані мрамрові відходи; мрамровий порошок; альтернативний заповнювач; сталий бетон; міцність на стиск; будівельні матеріали

Publisher's note

All claims expressed in this manuscript are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers.