




Article

Eco-Fired Bricks from Phosphate Mine Waste Rocks: The Effects of Marble Waste Powder on the Physical and Microstructural Properties

Ayoub Bayoussef ^{1,2} , Samira Moukannaa ^{3,*}, Mohamed Loutou ^{2,4}, Yassine Taha ³ , Mostafa Benzaazoua ³ 
and Rachid Hakkou ^{2,3,*}

¹ Higher School of Technology of Fkih Ben Salah, Sultane Moulay Sliman University of Beni-Mellal, Hay Tighnari, National Road to Casablanca N°11, P.O. Box 336, Beni-Mellal 23000, Morocco; a.bayoussef@usms.ac.ma

² Materials and Environmental Chemistry Laboratory (IMED-Lab), Faculty of Science and Technology Gueliz, Cadi Ayyad University, Avenue A. Elkhatabi, BP549, Marrakech 40000, Morocco

³ Geology and Sustainable Mining Institute (GSMI), Mohammad VI Polytechnic University, Lot 660. Hay Moulay Rachid, Ben Guerir 43150, Morocco

⁴ Laboratory of Molecular Chemistry, Materials and Environment (LCM2E), Department of Chemistry, Faculty Multidisciplinary Nador, University Mohamed Premier, B.P. 300, Selouane, Nador 62700, Morocco

* Correspondence: samira.moukannaa@um6p.ma (S.M.); r.hakkou@uca.ac.ma (R.H.)

Abstract: Nowadays, the global brick industry utilizes billions of cubic meters of clay soil annually, resulting in the massive consumption of non-renewable resources. This study explores the viability of utilizing red marl from phosphate mining waste rocks for fired brick production. Ecofriendly fired bricks produced from 100% side streams (red marly clays (RM) and marble waste powder (MWP)) were prepared, pressed, dried at 105 °C, and then fired at 1100 °C for 1 h. The effects of marble waste powder addition (up to 30 wt%) on the physical, mechanical, mineralogical, and microstructural properties of the fired bricks were explored. The main results show that fired bricks with high compressive strength of a maximum of 39 MPa could be prepared with a mixture of red marl and 10 wt% of marble waste powder. The thermal conductivity was decreased by marble waste addition (from 0 to 30%) and was reduced from 0.93 W/m.k to 0.53 W/m.k; however, the compressive strength was also decreased to reach a minimum of 17 MPa. The firing shrinkage and density were also reduced with 30% marble waste by 41% and 18%, respectively. Therefore, red marly clays and marble waste could be promising raw materials for eco-fired brick production.

Keywords: red marl; mine waste rock valorization; marble waste; fired bricks; thermal conductivity; density



Academic Editors: Francesco Baino, Pardeep Gianchandani, Enrico Fabrizio, Bartolomeo Megna and Manuela Ceraulo

Received: 21 March 2025

Revised: 21 April 2025

Accepted: 25 April 2025

Published: 1 May 2025

Citation: Bayoussef, A.; Moukannaa, S.; Loutou, M.; Taha, Y.; Benzaazoua, M.; Hakkou, R. Eco-Fired Bricks from Phosphate Mine Waste Rocks: The Effects of Marble Waste Powder on the Physical and Microstructural Properties. *Ceramics* **2025**, *8*, 48. <https://doi.org/10.3390/ceramics8020048>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The circular economy concept has become essential in addressing the growing challenges associated with waste and by-product generation, disposal, and management in various industries, including the mining sector. Traditional operating methods focusing on resource extraction, use, and disposal generally lead to environmental and economic concerns [1]. In contrast, the circular economy approach prioritizes resource recovery, reuse, and recycling to minimize waste and maximize resource utilization [2,3]. Adopting a circular economy can effectively tackle the issues related to solid waste management and help to preserve natural resources, especially for the mining industry, where large quantities of by-products and waste are generated [4,5].

Phosphate mining is one of the industries known for its continuous growth due to the increasing demand for phosphate ore owing to its crucial utilization in medicine and agriculture. During phosphate open-pit mining, large volumes of non-exploitable interlayers and cover layers are blasted and disposed of as waste rocks in stockpiles. Around 780 to 3120 Mt of waste rocks are estimated to be generated yearly and disposed of in large stockpiles at mining sites [1]. These waste rocks, comprising topsoil, flint, limestones, marl, and clays, are chemically stable; however, they can induce several environmental impacts associated with landscape degradation and reductions in arable land [6,7]. It is worth noting that the chemical and mineralogical composition of these waste rocks resembles that of several raw materials, such as clays, limestone, and aggregates used in the construction sector. This implies that the reuse of phosphate waste rocks as secondary available resources for construction material production could help to reduce the disposal of these by-products owing to the huge and increasing demand of the construction industry for resources, thus preserving natural resources.

Among these types of waste, clay-rich by-products from phosphate mining represent promising candidates as raw materials in construction. Numerous studies have been conducted in this regard, attempting to reuse clay-rich phosphate by-products for construction material manufacturing. Studies have demonstrated the suitability of producing ceramics and bricks using phosphate mining clay by-products, while similar studies have emphasized the necessity of fly ash incorporation into the clay by-product brick mix to improve the mechanical properties of the fired bricks [8,9]. Clay by-products from phosphate mining have demonstrated their viability as raw materials for different construction material types, e.g., as co-binders for ecological binder production, such as alkali-activated materials [10,11]; as supplementary cementitious materials to substitute clinkers [12]; and as binders for lightweight aggregates [13]. However, their chemical and mineralogical composition makes clay by-products from phosphate interlayers seem more suitable for fired brick or ceramic manufacturing. Previous studies in this regard have demonstrated the viability of this by-product for fired brick production, yet the firing shrinkage rate was high, varying from 16 to 21% [14]. Marble waste has been proven to increase the porosity, reduce the density, and decrease the shrinkage of fired bricks [15,16].

Marble waste is produced in large quantities during marble block cutting and polishing and is often disposed of near residential areas [17,18]. This side stream is mainly composed of calcium, magnesium, silicon, and aluminum oxides and is frequently generated as a fine powder, which can represent a source of several environmental issues, such as air pollution, reducing the fertility of natural soil, and surface water contamination [19,20]. Hence, its incorporation into fired bricks from phosphate waste rock might be an interesting research pathway to produce 100% side-stream-based fired bricks, while improving the firing shrinkage and density and conserving their outstanding mechanical properties.

The present study investigates the potential of manufacturing ecological fired bricks by combining red marly clay (RM) from phosphate by-products with marble waste powder (MWP). Although prior studies have established the individual potential of phosphate mine waste and marble waste powder for brick production, the synergistic combination of these two waste materials remains unexplored. Our innovative formulation was designed to achieve dual objectives: (1) enhancing the thermal insulation properties through the controlled porosity generated by marble powder's carbonate decomposition and (2) enabling effective waste valorization by capitalizing on the complementary characteristics of both industrial by-products. This approach simultaneously addresses two critical environmental challenges while advancing the development of sustainable construction materials with an improved insulating capacity, aligning with the circular economy principles. Marble waste was incorporated at different percentages (up to 30 wt%) (Table 1) in the brick mix.

The effects of marble addition on the phase formation, microstructure, density, shrinkage, thermal conductivity, and compressive strength of the fired bricks were studied.

Table 1. Experimental design.

Sample ID	Red Marl (wt %)	Marble Waste Powder (wt %)	Water Content (wt%)
MP 0	100	0	10
MP 10	90	10	10
MP 20	80	20	10
MP 30	70	30	10

2. Materials and Methods

The red marl (Figure 1) was sourced from phosphate mines in the Guantour Basin, Morocco, while marble powder (Figure 1) was obtained from a local industrial area in Marrakech, Morocco. Upon receipt, the materials underwent crushing and grinding to reduce the particle size, followed by sieving through a 200 μm sieve to retain the finer fraction.

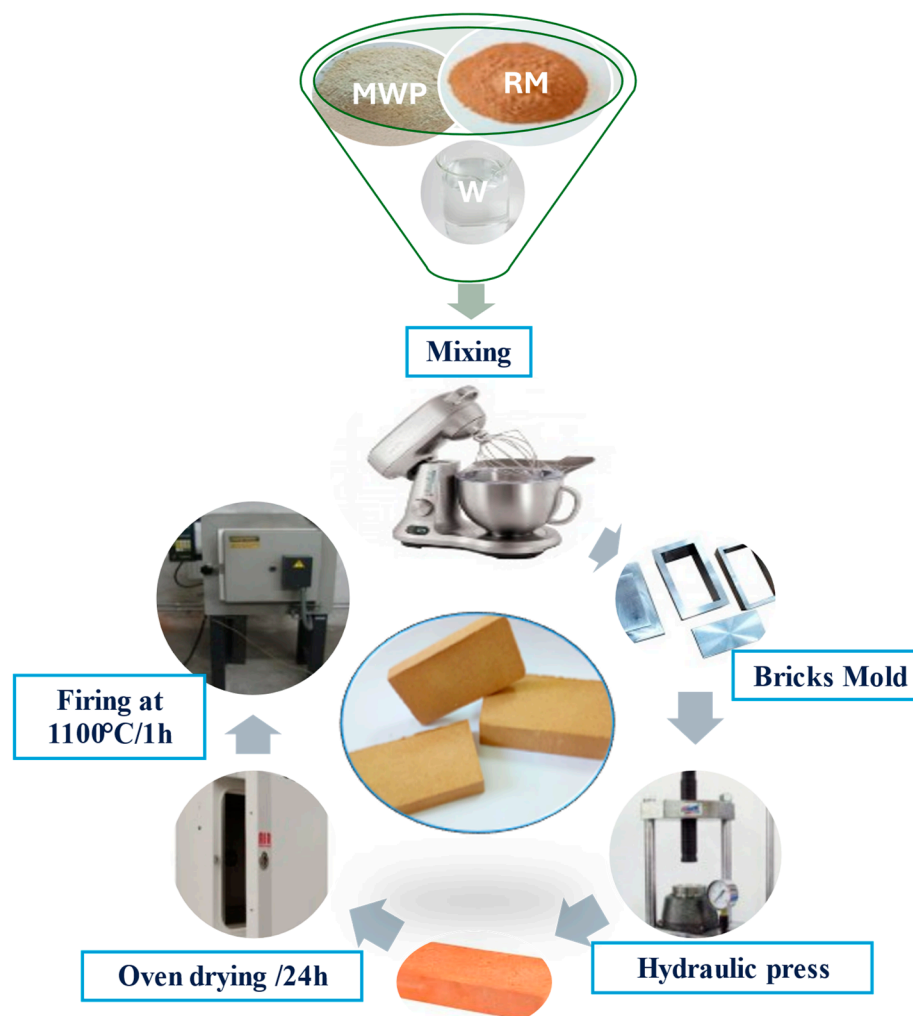


Figure 1. Fired brick production.

Both the raw marl and marble powder were characterized in terms of their mineralogical and chemical compositions.

Three different formulations were prepared using variable proportions of red marl and marble powder (10%, 20%, and 30% by weight), in addition to a reference brick composed of marl only (Table 1). Each formulation was thoroughly mixed for 10 min to ensure the even distribution of the powders. Next, water was gradually added (10% by weight of the dry mass) to the mixture to achieve the optimum moisture content for further processing. The moistened mixture was then pressed using a laboratory hydraulic press (Figure 1).

After pressing, the wet products were air-dried at ambient temperature for 48 h, followed by overnight oven drying at 105 °C. The final firing step involved introducing the dried products into a Nabertherm furnace and heating them to 1100 °C over 1 h, with a heating rate of 2 °C/min.

Characterization Techniques

The raw materials and final products were characterized using complementary analytical techniques to assess their chemical, mineralogical, structural, and thermal properties. X-ray fluorescence (XRF) spectroscopy with an Epsilon 4 instrument (Almelo, the Netherlands) and inductively coupled plasma optical emission spectroscopy (ICP-OES) using a device from PerkinElmer (Waltham, MA, USA) were employed to quantify major and trace elements, respectively, providing the basis for understanding their chemical compositions. Mineralogical phases were identified using X-ray diffraction (XRD) with a RIGAKU diffractometer (Tokyo, Japan) ($\lambda K\alpha = 1.54056 \text{ \AA}$), operating at 30 kV and 10 mA, with diffractograms recorded over a 2θ range of 5° to 70° (step size: 0.02°). These results complemented the chemical results, offering insights into the crystalline phases present. Thermogravimetric analysis (TGA) was conducted using the LABSYS Evo equipment (Lyon, France), heating the samples from room temperature to 1100 °C at 5 °C/min to evaluate their thermal stability and decomposition behavior, which correlated with the material's composition and structural characteristics. Finally, scanning electron microscopy (SEM) with a TESCAN VEGA3 instrument (Brno, Czech Republic), coupled with energy-dispersive X-ray spectroscopy (EDS), was employed to examine the microstructures and elemental distributions of the fired samples, linking the morphological observations to chemical and mineralogical data. These integrated techniques provided a comprehensive understanding of the samples' properties. In addition, the shaped samples were subjected to compressive strength measurements using an Instron 3369 (Norwood, MA, USA), at a speed of 0.1 mm/min. The results of the mechanical strength tests are reported as the mean values of three to five repeated tests. Water absorption was determined by weighing the samples before and after immersion in water for 24 h, according to standard European procedures, while density measurements were carried out using Archimedes' principle.

3. Results and Discussion

3.1. Characterization of Raw Materials

The XRD diagrams and mineralogical compositions of the marl and marble powder are illustrated in Figure 2. It reveals that the main phases constituting the marl material were dolomite (PDF#01-084-1208), quartz (PDF#00-046-1045), and palygorskite (PDF#96-900-5567), with the minor presence of illite (PDF#84e1220), fluoroapatite (PDF#00-015-0876), and hematite (PDF#00-033-0664). Marble powder contained calcite, albite, quartz, and a minor amount of dolomite [21]. The identified crystalline phases were in agreement with the microstructural analysis results (Figure 3) and the chemical composition (Tables 2 and 3).

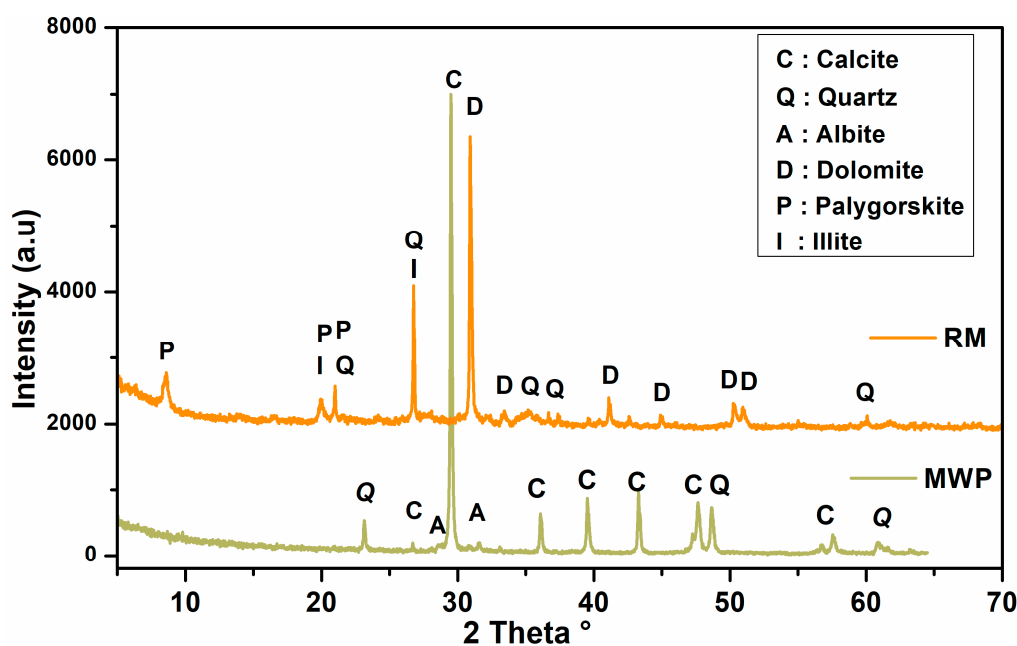


Figure 2. XRD of RM and MWP.

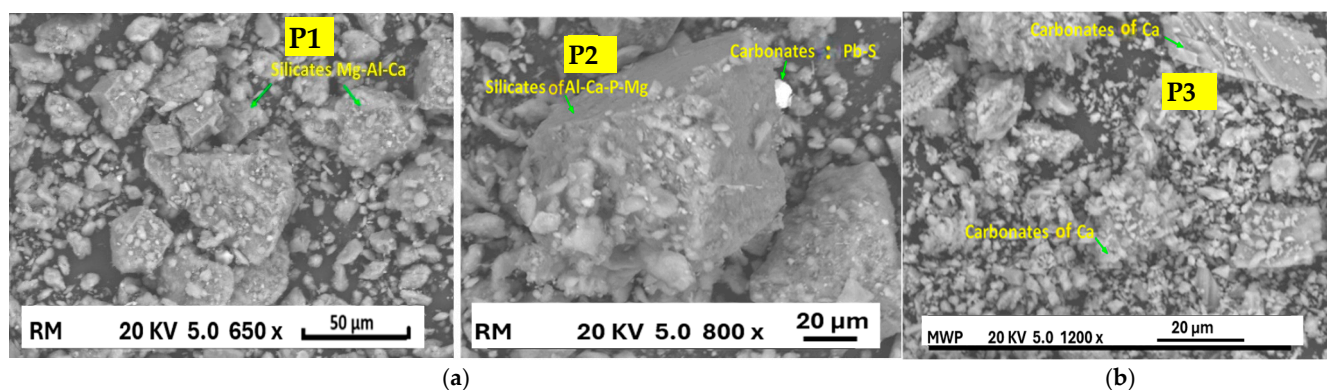


Figure 3. SEM analysis of raw materials of (a) RM and (b) MWP.

Table 2. Chemical analysis of RM and MWP.

Element (%)	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	K ₂ O	TiO ₂	P ₂ O ₅	S	Na ₂ O
RM	38.16	8.57	3.54	14.97	11.64	1.78	0.45	1.96	0.32	0.2
MWP	1.38	0.76	0.81	54.49	1.46	0.49	0.02	<0.01	0.57	0.16

Table 3. Chemical composition in terms of trace elements of RM and MWP.

Element (g/t)	As	Ba	Cd	Co	Cr	Cu	Ni	Pb	Zn
RM	24	133	<2	<8	718	114	172	<26	2270
MWP	90	21	<2	<8	111	81	101	<26	1009

The chemical analysis of RM and MWP through X-ray fluorescence spectroscopy (XRF) (Table 2) and inductively coupled plasma (ICP) analysis (Table 3) offers comprehensive insights into the elemental compositions of the raw materials employed in brick production. Notably, RM exhibits significant proportions of SiO₂, Al₂O₃, and Fe₂O₃, while MWP is characterized by the prominent presence of CaO. The high concentration of calcium oxide in MWP suggests a potential fluxing effect during the firing process, influencing

the sintering behavior, while the average presence of both CaO and MgO in RM will give rise to a complex interaction during heat treatment. Both act as fluxes, reducing the resulting melting temperature and improving the thermal and mechanical properties of the final product [22,23]. Furthermore, the ICP analysis reveals variations in trace elements like copper (Cu), nickel (Ni), and zinc (Zn) (Table 3). These variations may impact the final properties of the bricks, influencing factors such as the color, strength, and thermal conductivity. The distinct concentrations of copper and zinc in RM compared to MWP may contribute to divergent material behavior during firing, potentially affecting the mechanical and thermal performance of the resulting bricks [24,25]. Understanding these chemical subtleties is crucial in refining the manufacturing process and optimizing the performance of eco-friendly fired bricks.

The SEM examinations of the raw materials are displayed in Figure 3a,b. Both micrographs showed variability in the particle size and surface features. This heterogeneity is common in raw marls and affects the packing density and initial porosity during the sintering process. The irregular and granular morphology observed is characteristic of raw marls, reflecting minimal processing. Natural marls often exhibit aggregates of fine particles, which might have formed through compaction or natural weathering processes. The granular appearance and lack of a smooth particle surface might indicate the presence of non-marl materials or impurities, such as quartz, calcite, or organic matter. This statement corroborates the XRD-related results. The presence of silicates (Mg-Al-Ca), as also shown in Figure 3 and Table 4, indicates that the marl contains a mix of mineral phases, which play a significant role in its plasticity and fluxing during the sintering process.

Table 4. EDS results of the raw materials.

	Oxygen	Magnesium	Aluminium	Silicon	Calcium	Phosphorus	Carbon	Sum
P1	35.49	2.17	4.96	14.19	3.26	0	0	60.06
P2	62.67	1.79	1.13	3.35	23.84	4.31	0	97.10
P3	59.4	0	0	0	35.4	0	14.87	110.24

3.2. Thermal Analysis (TG-DTG)

A thermogravimetric analysis (TGA) was carried out to examine the weight loss of the marl and marble powder during high-temperature firing, as shown in Figure 4a. For the red marl, TG showed two main weight losses. The first (−5%) occurred between 30 °C and 180 °C due to the removal of adsorbed water, confirmed by a DTG endothermic peak between 100 °C and 200 °C (Figure 4b) [26]. A small endothermic peak at 300 °C and another small and large peak at 400 °C were attributed to the release of bound water in palygorskite [27] and to organic matter decomposition and the dehydroxylation of marl minerals, respectively [28]. The second major TG weight loss (−15%), observed between 558 °C and 864 °C, corresponded to the dihydroxylation of Mg-OH and Ca-OH groups; this phenomenon corresponds to the decomposition of dolomite and dihydroxylation of palygorskite, as explained by previous studies [29–31]. This was evidenced by two intense, overlapping DTG peaks between 600 °C and 700 °C [32]; see Figure 4b.

For the marble powder (Figure 4a), TG revealed minor weight loss (−5%) between 100 °C and 200 °C, linked to surface water evaporation [33], and significant weight loss (−45%) between 600 °C and 900 °C, attributed to CaCO₃ decomposition into CaO and CO₂ [34]. The DTG analysis confirmed these processes, showing a small endothermic peak at 600 °C for initial carbonate destabilization and an intense peak between 700 °C and 900 °C for the main decomposition of calcium carbonate [35]. These thermal behaviors highlight the structural and compositional differences between the two materials, with red marl undergoing more complex transformations due to its multi-mineral composition,

while the marble powder exhibits a dominant decomposition event related to its high carbonate content.

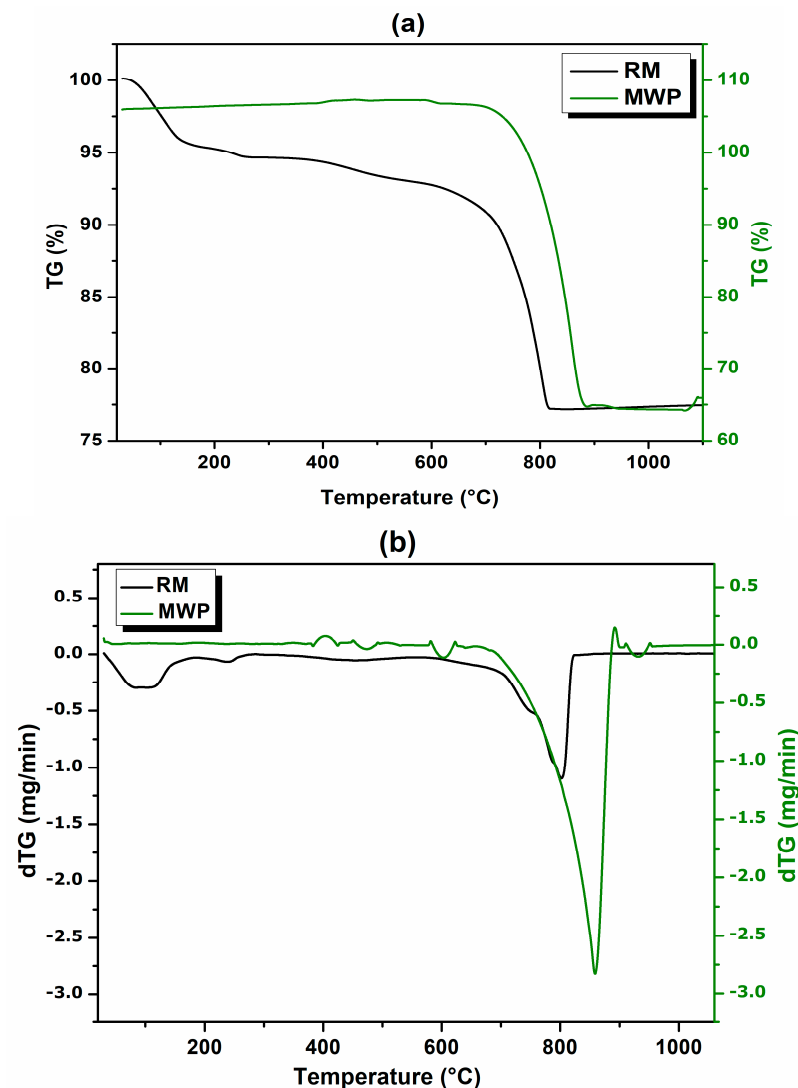


Figure 4. Thermal analysis: (a) TGA and (b) DTG of RM and MWP.

3.3. Physical Properties of Fired Bricks

The physical properties of building materials, such as the mechanical strength, density, water absorption, and thermal conductivity, are critical indicators of their quality and suitability for construction applications. In this study, cylindrical brick samples were tested, and the results were compared with those of a reference sample to assess the impact of marble powder substitution. The test results demonstrate the variations in the compressive strength, water absorption, density, and shrinkage with increasing substitution rates of marl with marble powder (Table 5 and Figure 5). The incorporation of marble powder significantly influenced these properties. The compressive strength decreased from 68.57 MPa in the reference sample to 17 MPa in bricks with 30% marble powder, while water absorption increased from 5% to 15.8%. These trends are primarily attributed to increased porosity, which will be further explored and discussed in the context of the microstructural analysis in the following section [36]. The XRD patterns and SEM micrographs show diminished amorphous halo signatures with higher marble powder content, potentially indicating the formation of fewer vitreous phases during firing. As these glassy phases normally enhance the structural integrity, their apparent reduction correlates with the observed mechanical

property trends. The slight reduction in the firing shrinkage of the bricks with higher marble powder content also supports the observed increase in porosity. This phenomenon is likely due to the decomposition of carbonates during firing, which leaves voids in the brick structure, as well as the reduced content of clay minerals in the mixture. Since clay minerals are primarily responsible for shrinkage during firing, their smaller proportion in marble-rich mixes further contributed to the diminished shrinkage. Similarly, the density of the bricks exhibited a slight decline with marble powder incorporation, reflecting the less compact microstructure caused by carbonate decomposition and subsequent pore formation. This effect was further amplified by the greater calcite content in the initial mix, which led to higher mass loss during firing (due to CO₂ release) and ultimately contributed to the lighter bricks. Normally, the density would be expected to show a more marked variation with MWP addition, similarly to the compressive strength and/or water absorption. This is probably due to the antagonistic effect of sintering with the formation of porosity, leading to a more or less compacted structure.

Table 5. Physical and mechanical properties of brick samples.

MWP Content (%)	Water Absorption (%)	Density (g/cm ³)	Shrinkage (%)	Compressive Strength (MPa)	LOI (%)
10.00	8.91	1.77	3.16	39.74	22.88
20.00	13.19	1.75	2.46	29.40	25.26
30.00	15.80	1.71	1.76	17.09	27.67

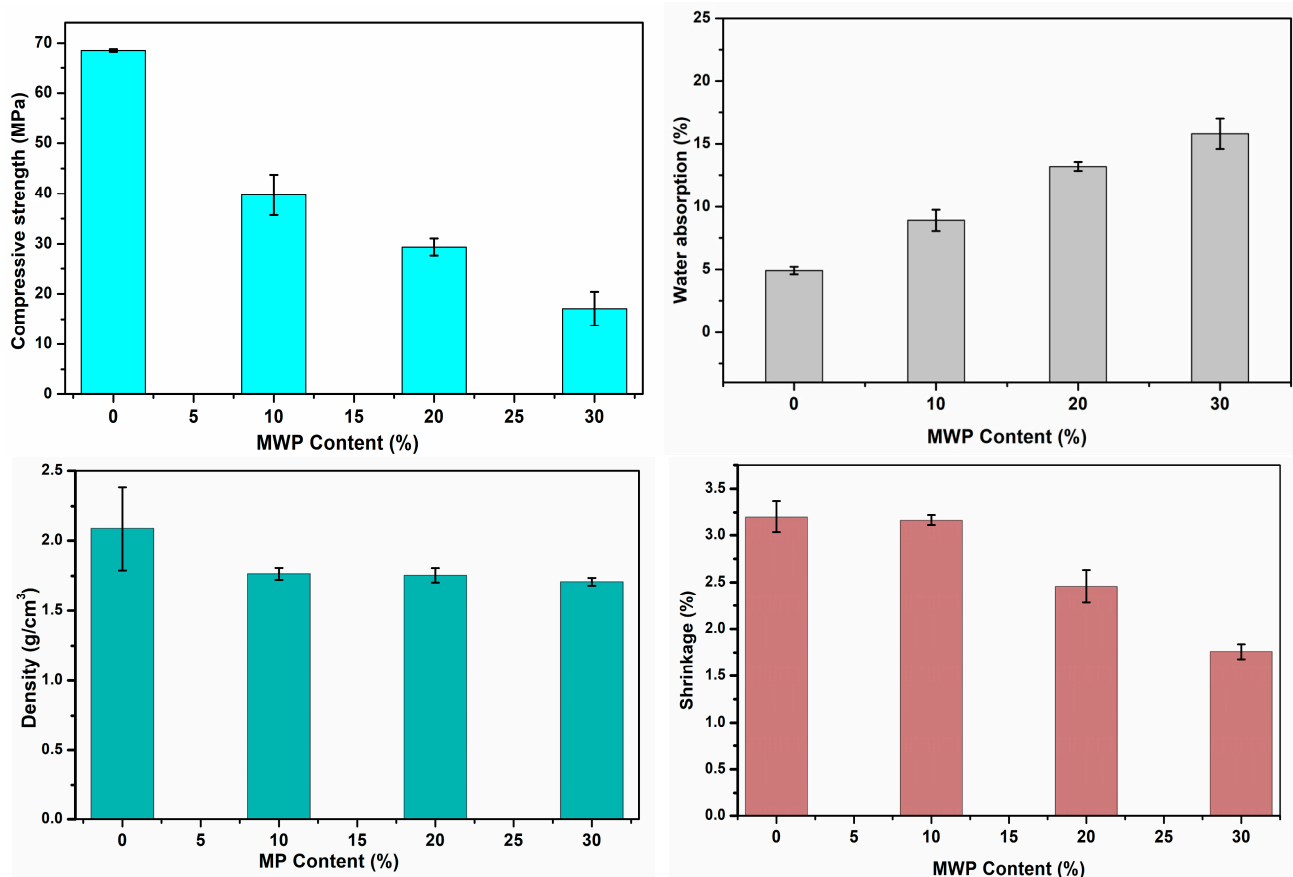


Figure 5. Physical properties of fired bricks.

Figure 6 illustrates the relationships among various sintered brick properties, revealing a strong correlation between the compressive strength and water absorption ($R^2 = 0.93$) and between the loss on ignition (LOI) and firing shrinkage ($R^2 = 0.8$). These findings align with the observed trends: lower compressive strength corresponds to higher water absorption, while reduced loss on ignition, potentially influenced by other factors, is linked to decreased shrinkage due to the bricks' microstructural characteristics [37]. It is important to note that these correlations, including factors like the pore distribution, crack propagation, and phase transitions during firing, are supported by the data but may also involve additional influences.

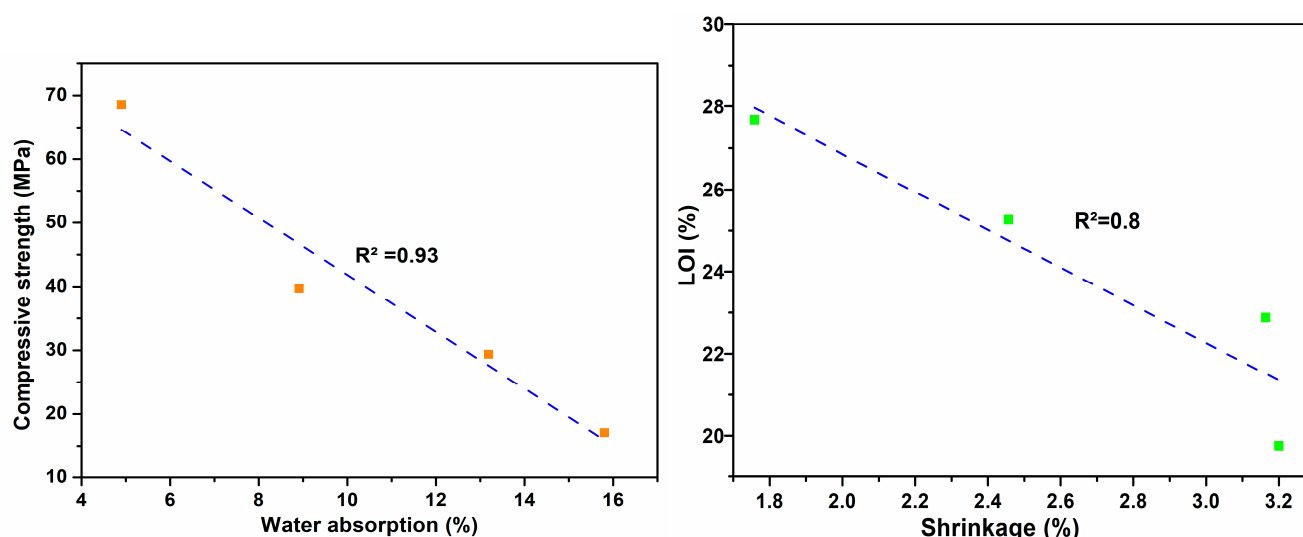
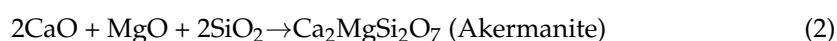
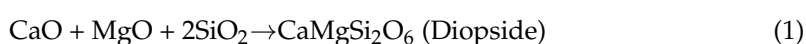


Figure 6. Correlations between physical properties.

Moreover, the integration of carbonate-rich marble powder resulted in reduced thermal conductivity compared to the reference products, as depicted in Figure 7. This decline in thermal conductivity can be attributed to the increased porosity of the bricks, which inherently influences their thermal properties [38,39]. Porosity introduces voids in the ceramic matrix, which are typically filled with air or another gas [40]. Air has significantly lower thermal conductivity (~ 0.024 W/m·K) compared to a solid ceramic material. Air pockets act as thermal insulators, disrupting the continuous solid pathways for heat transfer and scattering heat carriers [41–43]. Consequently, the thermal insulation properties were significantly enhanced, showcasing a remarkable improvement of up to 42%. This finding underscores the potential of marble powder incorporation to enhance the thermal performance of fired bricks, thereby contributing to improved energy efficiency and overall sustainability in construction applications.

3.4. Microstructural Analysis of Fired Bricks

The mineralogical characterization results of the manufactured bricks are displayed in Figure 8. It reveals significant mineralogical transformations during firing. Neoformed phases such as diopside (PDF#00-041-1370), akermanite (COD#96-900-6116), gehlenite (PDF#01-089-5917), enstatite (COD#96-900-5543), and rondorfite were identified, indicating reactions between the original minerals and the decomposition products of carbonates, among other components, during sintering.



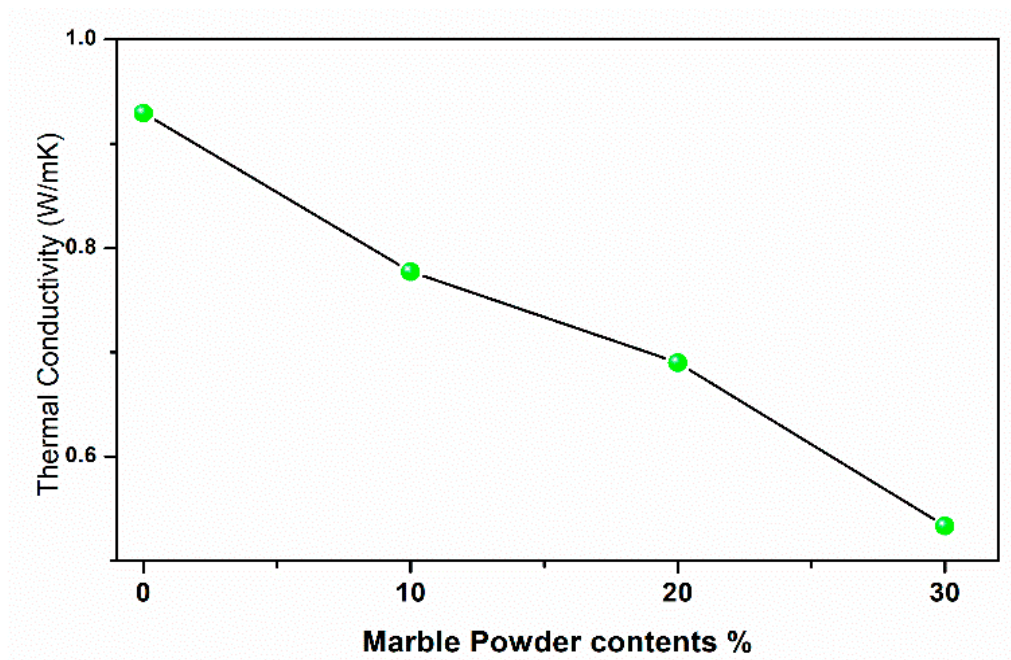
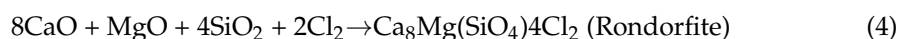


Figure 7. Thermal conductivity of fired bricks.

The formation of gehlenite and akermanite can be attributed to reactions between calcite (CaCO_3 from marble powder) and silica-rich phases like quartz or illite in the marl [32]. Similarly, the decomposition of dolomite and calcite at high temperatures liberates CaO and CO_2 [44], with the CaO reacting with aluminosilicates to form gehlenite and diopside. Palygorskite undergoes dehydroxylation, releasing MgO , which contributes to enstatite and diopside formation, while illite decomposition primarily yields K_2O [45,46]. Rondorfite formation is likely a result of interactions involving fluorapatite, providing fluorine for stabilization, and calcium and magnesium from calcite and dolomite. The presence of hematite may also play a catalytic role in phase formation [47,48].

These mineralogical changes are directly linked to the physical properties of the bricks, highlighting the interplay between phase development and structural integrity during sintering. The newly formed phases, such as diopside and akermanite, contribute significantly to improving the thermal and mechanical stability of the bricks by providing a robust crystalline framework. These phases are particularly valuable in enhancing their durability, making them suitable for structural applications.

However, the observed reduction in vitreous phases, coupled with the formation of micropores and cracks, as observed in the SEM images (Figures 9 and 10), introduces structural vulnerabilities. This phenomenon correlates with decreased compressive strength and increased water absorption as the marble powder content increases. The decomposition of carbonates plays a pivotal role, leaving voids that elevate the porosity and weaken the brick's matrix. This increased porosity accounts for the decline in density and firing shrinkage, which are critical parameters in evaluating the quality and performance of sintered bricks.

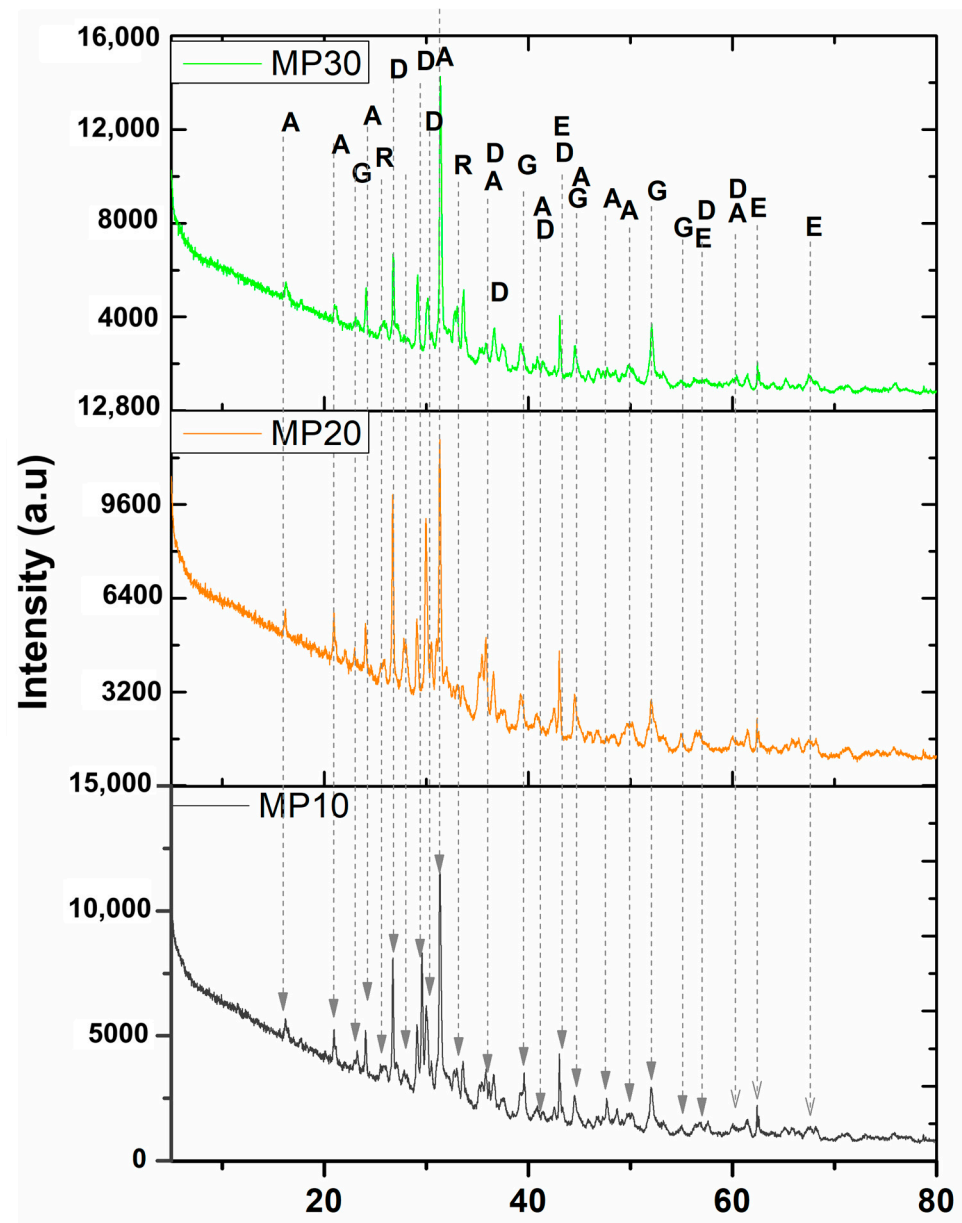


Figure 8. X-ray crystallography spectra of fired bricks.

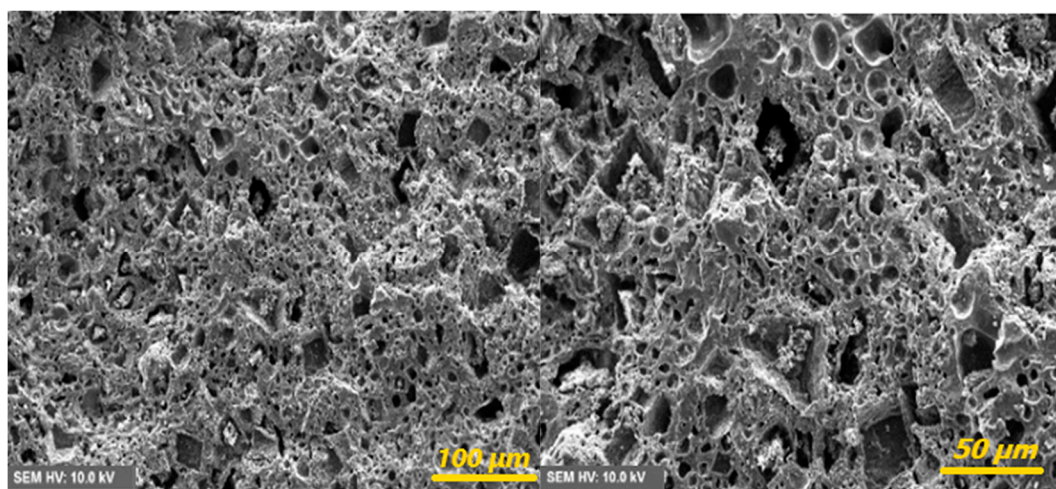


Figure 9. SEM of reference bricks produced with RM.

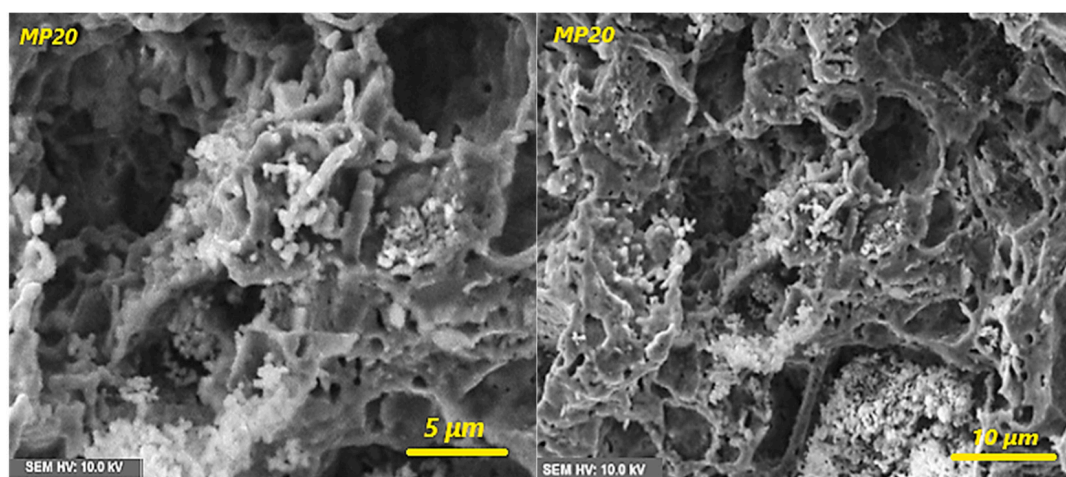


Figure 10. SEM of bricks containing 20% of MWP.

Therefore, the mineralogical evolution during firing exerts a dual influence: while newly formed stable phases enhance the thermal and mechanical properties, the structural weaknesses induced by porosity counteract these benefits. Achieving an optimal balance between these opposing effects is essential in tailoring the sintering process to produce bricks with desired properties. These findings emphasize the need for a detailed understanding of the mineral interactions and decomposition mechanisms to effectively valorize marl-rich mine by-products and maximize their potential in sustainable brick production.

A scanning electron microscope (SEM) was employed to investigate the internal microstructural characteristics of the bricks under study. The resulting micrographs revealed prominent microstructural features and exhibited heterogeneous porosity within the samples. Additionally, the micrographs (refer to Figures 9 and 10) depicted the presence of crystalline particles with varying textures and sizes, further highlighting the complexity of the brick microstructure. The observed heterogeneous porosity can be attributed to the decomposition and subsequent loss of carbonates within the samples. This decomposition leads to the formation of voids and irregularities within the brick matrix, which compromise the overall structural integrity and result in decreased compressive strength and density. These findings are corroborated by the SEM micrographs, which illustrate the presence of a highly irregular and porous microstructure.

The diverse textures and sizes of the crystalline particles observed in the micrographs suggest variations in their composition and distribution across the bricks. These variations can stem from two primary factors: the inherently heterogeneous nature of the raw mine by-products used (marl lithologies and marble waste powders) and the firing conditions during sintering. Notably, these differences in crystalline structure and porosity influence how stress is distributed across the brick matrix and contribute to the material's performance under various loading and environmental conditions.

Moreover, the microstructural features observed, such as the development of micropores and cracks and the presence of non-uniform carbonate decomposition, further explain the changes in the bricks' physical properties. These porosities act as stress concentrators, exacerbating mechanical weaknesses, leading to reduced compressive strength, and increasing the water absorption rate [40,49]. Understanding these microstructural characteristics can provide insights for the tailoring of the sintering process or the modification of the raw material composition to optimize these sustainable bricks' mechanical and physical properties [50,51].

These observations underscore the importance of monitoring mineralogical transformations and their microstructural effects during sintering to better control the performance and functionality of mine by-products valorized into construction materials.

Overall, the SEM analysis provides valuable insights into the intricate microstructures of the bricks, shedding light on the factors influencing their mechanical behavior and highlighting potential avenues for optimization in future manufacturing processes.

4. Conclusions

In conclusion, this study demonstrates the successful development of environmentally friendly bricks with enhanced mechanical properties and thermal insulation by utilizing waste-derived raw materials from the mining industry. The comprehensive characterization and experimental results confirm the feasibility and effectiveness of integrating red marl from phosphate by-products and marble waste powder into the brick production process. This innovative approach addresses pressing environmental challenges by valorizing mining waste, reducing the reliance on natural resources traditionally used in brick manufacturing and minimizing waste disposal issues.

The findings highlight that the incorporation of marble waste powder and its associated mineralogical transformations during firing significantly influence the physical and mechanical properties of the resulting bricks. The produced bricks exhibited competitive compressive strength and thermal insulation performance, demonstrating their potential to meet contemporary construction standards while serving as a sustainable alternative to conventional brick materials. This approach not only reduces the dependency on natural marl but also offers both ecological and economic advantages by mitigating the environmental impacts of mining waste.

This study emphasizes the critical role of interdisciplinary research in addressing sustainability challenges and advancing innovative solutions for the construction industry. The findings pave the way for the development of advanced, eco-friendly building materials that align with global sustainability goals and efforts to reduce environmental footprints.

While the lab-scale bricks showed no bloating defects, industrial-scale production with thicker formats may experience CO₂ entrapment during calcite decomposition, potentially causing internal pressures and structural defects [52]. This risk rises with both the brick thickness and marble powder (MWP) content. Future research should focus on (1) formulation optimization, particularly in controlling the marble powder (MWP) particle size distribution to mitigate rapid gas release through more uniform carbonate decomposition; (2) optimizing raw material formulations, particularly in determining the optimal marble powder (MWP) dosage and firing regime to balance porosity development and bloating risks; (3) scaling up production processes for industrial applications—our planned tests will systematically evaluate the maximum MWP incorporation levels before defect formation, temperature thresholds for controlled decarbonation, and firing cycle modifications to facilitate gradual CO₂ release [53,54]; and (4) assessing long-term durability under diverse environmental conditions. These efforts will ensure the safe, widespread adoption of this sustainable building material, supporting greener construction practices.

Author Contributions: Conceptualization, A.B. and R.H.; methodology, A.B. and R.H.; software, A.B. and Y.T.; validation, R.H.; formal analysis, A.B. and S.M.; investigation, A.B., S.M., M.L. and Y.T.; resources, R.H.; data curation, A.B. and M.L.; writing—original draft preparation, A.B., S.M. and M.L.; writing—review and editing, A.B., S.M., M.L., Y.T., M.B. and R.H.; visualization, A.B., M.L. and M.B.; supervision, R.H.; project administration, R.H.; funding acquisition, R.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the OCP Foundation through the APRD Research Program, grant number Eco-MAT 21–24.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author(s).

Acknowledgments: The authors would like to thank the Moroccan Ministry of Higher Education, Scientific Research and Innovation and the OCP Foundation for funding this work through the APRD Research Program under the Eco-MAT 21–24 grant.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

RM Red Marl
MWP Marble Waste Powder

References

- Beniddar, H.; El Machi, A.; El Abbassi, F.-E.; Taha, Y.; Benzaazoua, M.; Hakkou, R. Sustainable utilization of phosphate mine waste rocks as sand substitutes in cement mortar production. *Constr. Build. Mater.* **2024**, *438*, 136949. [\[CrossRef\]](#)
- Hu, S.; Wang, J.; Xia, X. Study on development of circular economy in Hefei. In Proceedings of the 3rd International Conference on Environmental Technology and Knowledge Transfer, Hefei, China, 13–14 May 2010.
- Yuan, H.; Wang, J. A system dynamics model for determining the waste disposal charging fee in construction. *Eur. J. Oper. Res.* **2014**, *237*, 988–996. [\[CrossRef\]](#)
- Olejarczyk, M.; Rykowska, I.; Urbaniak, W. Management of Solid Waste Containing Fluoride—A Review. *Materials* **2022**, *15*, 3461. [\[CrossRef\]](#) [\[PubMed\]](#)
- Pandey, V.; Panda, S.K.; Singh, V.K. Preparation and characterization of high-strength insulating porous bricks by reusing coal mine overburden waste, red mud and rice husk. *J. Clean. Prod.* **2024**, *469*, 143134. [\[CrossRef\]](#)
- Moukannaa, S.; Bagheri, A.; Benzaazoua, M.; Sanjayan, J.G.; Pownceby, M.I.; Hakkou, R. Elaboration of alkali activated materials using a non-calcined red clay from phosphate mines amended with fly ash or slag: A structural study. *Mater. Chem. Phys.* **2020**, *256*, 123678. [\[CrossRef\]](#)
- Oubaha, S.; El Machi, A.; Mabroum, S.; Taha, Y.; Benzaazoua, M.; Hakkou, R. Recycling of phosphogypsum and clay by-products from phosphate mines for sustainable alkali-activated construction materials. *Constr. Build. Mater.* **2024**, *411*, 134262. [\[CrossRef\]](#)
- Mouih, K.; Hakkou, R.; Taha, Y.; Benzaazoua, M. Performances of compressed stabilized bricks using phosphate waste rock for sustainable construction. *Constr. Build. Mater.* **2023**, *388*, 131577. [\[CrossRef\]](#)
- Bayoussef, A.; Oubani, M.; Loutou, M.; Taha, Y.; Benzaazoua, M.; Manoun, B.; Hakkou, R. Manufacturing of high-performance ceramics using clays by-product from phosphate mines. *Mater. Today Proc.* **2021**, *37*, 3994–4000. [\[CrossRef\]](#)
- Gavali, H.R.; Ralegaonkar, R.V. Design development of sustainable alkali-activated bricks. *J. Build. Eng.* **2020**, *30*, 101302. [\[CrossRef\]](#)
- Boughriet, A.; Allahdin, O.; Poumaye, N.; Doyemet, G.; Tricot, G.; Revel, B.; Ouddane, B.; Wartel, M. Alkali-Activated Brick Aggregates as Industrial Valorized Wastes: Synthesis and Properties. *Ceramics* **2023**, *6*, 108. [\[CrossRef\]](#)
- Bahhou, A.; Taha, Y.; El Khessaimi, Y.; Idrissi, H.; Hakkou, R.; Amalik, J.; Benzaazoua, M. Use of phosphate mine by-products as supplementary cementitious materials. *Mater. Today Proc.* **2021**, *37*, 3781–3788. [\[CrossRef\]](#)
- Loutou, M.; Hajjaji, M.; Mansori, M.; Favotto, C.; Hakkou, R. Phosphate sludge: Thermal transformation and use as lightweight aggregate material. *J. Environ. Manag.* **2013**, *130*, 354–360. [\[CrossRef\]](#)
- Loutou, M.; Taha, Y.; Benzaazoua, M.; Daafi, Y.; Hakkou, R. Valorization of clay by-product from moroccan phosphate mines for the production of fired bricks. *J. Clean Prod.* **2019**, *229*, 169–179. [\[CrossRef\]](#)
- Ahmad, S.; Shah, M.U.H.; Ullah, A.; Shah, S.N.; Rehan, M.S.; Khan, I.A.; Ahmad, M.I. Sustainable Use of Marble Waste in Industrial Production of Fired Clay Bricks and Its Employment for Treatment of Flue Gases. *ACS Omega* **2021**, *6*, 22559–22569. [\[CrossRef\]](#)
- Galetakis, M.; Soultana, A. A review on the utilisation of quarry and ornamental stone industry fine by-products in the construction sector. *Constr. Build. Mater.* **2016**, *102*, 769–781. [\[CrossRef\]](#)

17. Tunc, E.T. Recycling of marble waste: A review based on strength of concrete containing marble waste. *J. Environ. Manag.* **2019**, *231*, 86–97. [[CrossRef](#)] [[PubMed](#)]
18. Khan, M.; Khan, B.; Shahzada, K.; Khan, S.; Wahab, N.; Ahmad, M.I. Conversion of Waste Marble Powder into a Binding Material. *Civ. Eng. J.* **2020**, *6*, 431–445. [[CrossRef](#)]
19. Das, D.; Gołabiewska, A.; Rout, P.K. Geopolymer bricks: The next generation of construction materials for sustainable environment. *Constr. Build. Mater.* **2024**, *445*, 137876. [[CrossRef](#)]
20. Wang, Y.; Xiao, J.; Zhang, J.; Duan, Z. Mechanical Behavior of Concrete Prepared with Waste Marble Powder. *Sustainability* **2022**, *14*, 4170. [[CrossRef](#)]
21. Vardhan, K.; Goyal, S.; Siddique, R.; Singh, M. Mechanical properties and microstructural analysis of cement mortar incorporating marble powder as partial replacement of cement. *Constr. Build. Mater.* **2015**, *96*, 615–621. [[CrossRef](#)]
22. Rehman, M.U.; Ahmad, M.; Rashid, K. Influence of fluxing oxides from waste on the production and physico-mechanical properties of fired clay brick: A review. *J. Build. Eng.* **2020**, *27*, 100965. [[CrossRef](#)]
23. Eliche-Quesada, D.; Leite-Costa, J. Use of bottom ash from olive pomace combustion in the production of eco-friendly fired clay bricks. *Waste Manag.* **2016**, *48*, 323–333. [[CrossRef](#)] [[PubMed](#)]
24. Kazmi, S.M.S.; Munir, M.J.; Patnaikuni, I.; Wu, Y.F.; Fawad, U. Thermal performance enhancement of eco-friendly bricks incorporating agro-wastes. *Energy Build* **2018**, *158*, 1117–1129. [[CrossRef](#)]
25. Dai, Z.; Wu, Y.; Hu, L.; Zhang, W.; Mao, L. Evaluating physical-mechanical properties and long periods environmental risk of fired clay bricks incorporated with electroplating sludge. *Constr. Build. Mater.* **2019**, *227*, 116716. [[CrossRef](#)]
26. Hofmann, E.; Németh, T.; Bidló, A. Thermal analysis of soils formed on limestone in the Bükk Mountains, North Hungary. *J. Agrokémia És Talajt* **2018**, *67*, 5–22. [[CrossRef](#)]
27. Wang, S.; Gaaney, L.; Wang, X.; Mackinnon, I.D.R.; Xi, Y. Influence of palygorskite on in-situ thermal behaviours of clay mixtures and properties of fired bricks. *Appl. Clay Sci.* **2022**, *216*, 106384. [[CrossRef](#)]
28. Collard, F.-X.; Blin, J. A review on pyrolysis of biomass constituents: Mechanisms and composition of the products obtained from the conversion of cellulose, hemicelluloses and lignin. *J. Renew. Sustain. Energy Rev.* **2014**, *38*, 594–608. [[CrossRef](#)]
29. Carazo, E.; Borrego-Sánchez, A.; García-Villén, F.; Sánchez-Espejo, R.; Viseras, C.; Cerezo, P.; Aguzzi, C. Adsorption and characterization of palygorskite-isoniazid nanohybrids. *Appl. Clay Sci.* **2018**, *160*, 180–185. [[CrossRef](#)]
30. Kuang, W.; Facey, G.A.; Detellier, C. Dehydration and rehydration of palygorskite and the influence of water on the nanopores. *Clays Clay Miner.* **2004**, *52*, 635–642. [[CrossRef](#)]
31. Dong, W.; Lu, Y.; Wang, W.; Zong, L.; Zhu, Y.; Kang, Y.; Wang, A. A new route to fabricate high-efficient porous silicate adsorbents by simultaneous inorganic-organic functionalization of low-grade palygorskite clay for removal of Congo red. *Microporous Mesoporous Mater.* **2019**, *277*, 267–276. [[CrossRef](#)]
32. Harrati, A.; Arkame, Y.; Manni, A.; Aqdim, S.; Zmemla, R.; Chari, A.; El Bouari, A.; Hassani, I.-E.E.A.E.; Sdiri, A.; Hassani, F.O.; et al. Akermanite-based ceramics from Moroccan dolomite and perlite: Characterization and in vitro bioactivity assessment. *Open Ceram.* **2022**, *10*, 100276. [[CrossRef](#)]
33. Pramono, E.; Pratiwi, W.; Wahyuningrum, D.; Radiman, C.L. Thermal properties of Bentonite Modified with 3-aminopropyltrimethoxysilane. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *333*, 12084. [[CrossRef](#)]
34. Qian, H.; Kai, W.; Hongde, X. A novel perspective of dolomite decomposition: Elementary reactions analysis by thermogravimetric mass spectrometry. *J. Thermochim. Acta* **2019**, *676*, 47–51. [[CrossRef](#)]
35. Scott, S.A.; Dennis, J.S.; Davidson, J.F.; Hayhurst, A.N. Thermogravimetric measurements of the kinetics of pyrolysis of dried sewage sludge. *J. Fuel* **2006**, *85*, 1248–1253. [[CrossRef](#)]
36. Zhuginissov, M.T.; Nurlybayev, R.E.; Orynbekov, Y.S.; Zhumadilova, Z.O.; Khamza, Y.Y.; Bulenbayev, M.Z. The Influence of the Burning Environment on the Properties of Ceramic Products Based on Fusible Raw Materials. *Ceramics* **2023**, *6*, 872–885. [[CrossRef](#)]
37. Ozturk, S.; Sutcu, M.; Erdogmus, E.; Gencel, O. Influence of tea waste concentration in the physical, mechanical and thermal properties of brick clay mixtures. *Constr. Build. Mater.* **2019**, *217*, 592–599. [[CrossRef](#)]
38. Singh, D.; Kumar, R.; Nighot, N.S.; Rajput, A.; Prajapati, A.; Singh, B.K.; Kirgiz, M.S.; Srinivasaraonaik, B.; Mishra, R.K.; Khan, S.; et al. A comprehensive review on valorisation of octal by-product as supplementary admixtures in the production of fired and unfired bricks. *Constr. Build. Mater.* **2023**, *408*, 133641. [[CrossRef](#)]
39. Munir, M.J.; Abbas, S.; Nehdi, M.L.; Kazmi, S.M.S.; Khitab, A. Development of Eco-Friendly Fired Clay Bricks Incorporating Recycled Marble Powder. *J. Mater. Civ. Eng.* **2018**, *30*, 04018069. [[CrossRef](#)]
40. Kadir, A.A.; Mohajerani, A. Effect of heating rate on gas emissions and properties of fired clay bricks and fired clay bricks incorporated with cigarette butts. *Appl. Clay Sci.* **2015**, *104*, 269–276. [[CrossRef](#)]
41. Wang, C.; Wang, J.; Li, Q.; Xu, S.; Jiang, J. A review on recent development of foam Ceramics prepared by particle-stabilized foaming technique. *Adv. Colloid Interface Sci.* **2024**, *330*, 103198. [[CrossRef](#)]

42. Evcin, A.; Ersoy, B.; Çiftçi, H. Utilization of Marble and Boron Waste in Brick Products. *Int. J. Comput. Exp. Sci. Eng.* **2019**, *5*, 19–22. [\[CrossRef\]](#)
43. Makrygiannis, I.; Karalis, K. Optimizing Building Thermal Insulation: The Impact of Brick Geometry and Thermal Coefficient on Energy Efficiency and Comfort. *Ceramics* **2023**, *6*, 1449–1466. [\[CrossRef\]](#)
44. Gunasekaran, S.; Anbalagan, G. Thermal decomposition of natural dolomite. *Bull. Mater. Sci.* **2007**, *30*, 339–344. [\[CrossRef\]](#)
45. Bozkaya, Ö.; Yalçın, H. Mineral Chemistry of Low-Temperature Phyllosilicates in Early Paleozoic Metaclastic Rocks, Eastern Tauride Belt, Türkiye. *Minerals* **2022**, *12*, 1088. [\[CrossRef\]](#)
46. Meunier, A.; Velde, B. *Illite: Origins, Evolution and Metamorphism*; Springer: Berlin/Heidelberg, Germany, 2010.
47. Li, M.; Su, P.; Guo, Y.; Zhang, W.; Mao, L. Effects of SiO₂, Al₂O₃ and Fe₂O₃ on leachability of Zn, Cu and Cr in ceramics incorporated with electroplating sludge. *J. Environ. Chem. Eng.* **2017**, *5*, 3143–3150. [\[CrossRef\]](#)
48. Souza, A.E.; Teixeira, S.R.; Santos, G.T.A.; Costa, F.B.; Longo, E. Reuse of sugarcane bagasse ash (SCBA) to produce ceramic materials. *J. Environ. Manag.* **2011**, *92*, 2774–2780. [\[CrossRef\]](#)
49. Aouba, L.; Bories, C.; Coutand, M.; Perrin, B.; Lemerrier, H. Properties of fired clay bricks with incorporated biomasses: Cases of Olive Stone Flour and Wheat Straw residues. *Constr. Build. Mater.* **2016**, *102*, 7–13. [\[CrossRef\]](#)
50. Menezes, R.R.; Ferreira, H.S.; Neves, G.A.; de L. Lira, H.; Ferreira, H.C. Use of granite sawing wastes in the production of ceramic bricks and tiles. *J. Eur. Ceram. Soc.* **2005**, *25*, 1149–1158. [\[CrossRef\]](#)
51. Subari, F.E. Utilization of Marble and Limestone Wastes for Making the Eksposed Bricks Based Synthetic Wollastonite. *J. Teknol. Miner. Dan Batubara* **2016**, *12*, 171–178.
52. Cultrone, G.; Rodriguez-Navarro, C.; Sebastian, E.; Cazalla, O.; De La Torre, M.J. Carbonate and silicate phase reactions during ceramic firing. *J. Eur. J. Mineral.* **2001**, *13*, 621–634. [\[CrossRef\]](#)
53. Karaman, S.; Ersahin, S.; Gunal, H. Firing temperature and firing time influence on mechanical and physical properties of clay bricks. *J. Sci. Ind. Res.* **2006**, *65*, 153–159.
54. Tsega, E. Effects of Firing Time and Temperature on Physical Properties of Fired Clay Bricks. *Am. J. Civ. Eng.* **2017**, *5*, 21. [\[CrossRef\]](#)

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.