Eggshell Powder from Moroccan Sources: A Promising Partial Replacement for Cement in Eco-Friendly Concrete

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Abstract. The cement industry is one of the largest contributors to global CO_2 emissions, accounting for approximately 7–8% of total emissions due to its energy-intensive production process and heavy reliance on clinker. In response to increasing environmental concerns, the development of low-carbon construction materials has become a major research focus. Simultaneously, the food industry generates vast quantities of eggshell waste, estimated at over 70 million tons globally per year. In Morocco, eggshells are commonly discarded in household or food processing waste streams, causing environmental issues due to their slow biodegradation and potential for microbial growth. However, eggshells are composed of more than 90% calcium carbonate ($CaCO_3$), giving them chemical similarity to limestone, a key component in cement. This study investigates the feasibility of using locally sourced, ground, non-calcined Moroccan Eggshell Powder (ESP) as a Supplementary Cementitious Material (SCM) to partially replace Portland cement in mortar formulations. ESP was incorporated at replacement levels of 10%, 15%, 20%, and 30% by weight. The impact of ESP on physical properties such as water absorption, bulk density, and workability was assessed using standard procedures, including the Abrams cone method. Thermal conductivity was measured using the Hot Disk method. Compressive strength was evaluated at 7 and 90 days of curing. The findings demonstrate that ESP can reduce cement demand, valorize biogenic waste, and enhance the sustainability of construction materials, with performance influenced by the replacement percentage.

1 Introduction

Portland cement production is a critical driver of climate change, emitting 0.83–0.93 tons of CO_2 per ton of cement produced [1]. This sector contributes 7–8% of global anthropogenic CO_2 emissions, with ~60% stemming from limestone calcination (equation 1) and 40% from fossil fuel combustion [2]. Alarmingly, annual cement production (~4.3 Gt in 2021) is projected to rise 12–23% by 2050, exacerbating its carbon footprint unless sustainable alternatives are adopted.

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$$CaCO_3 \rightarrow CaO + CO_2 \quad (1)$$

To align with the Paris Agreement's 1.5°C target [3], the construction industry must reduce cement-related emissions by 50% before 2030. While conventional Supplementary Cementitious Materials (SCMs) like fly ash (20–30% substitution potential) and slag offer partial solutions, their geographic scarcity (e.g., limited coal plants in Morocco) and quality variability hinder universal application [4]. This underscores the urgency to develop locally sourced, low-carbon SCMs compatible with circular economy principles.

In Morocco, cement production reached 21 million tons in 2022 [5], emitting an estimated 16.8 million tons of CO_2 (assuming 0.83 tCO_2/t cement). Unlike industrialized nations, Morocco lacks access to conventional SCMs like slag (steel industry byproducts) or high-quality fly ash. This creates a critical dependency on clinker and imports, increasing both costs and emissions.

Simultaneously, Morocco's agro-industrial sector produces approximately 6.6 billion eggs annually [6], corresponding to nearly 396,000 tons of eggs. With eggshells accounting for about 11% of the egg weight [7], this translates into an estimated 43,000–44,000 tons of eggshell waste per year, equivalent to nearly 38,000 tons of $CaCO_3$. - enough to potentially replace 3-5% of national cement demand. Currently, 90% is landfilled, where its slow biodegradation releases CH_4 (GWP 28× CO_2) and attracts pests (Schematic of eggshell waste composition in Fig 1). A. Suehail et al. [8] specifies that « In landfills, eggshells decompose slowly under anaerobic conditions, releasing methane—a potent greenhouse gas—into the atmosphere. Additionally, improperly discarded eggshells can attract pests, such as rodents and insects. ». On the other hand, another recent study by S. Owuamanam et al [9] state that "The majority of waste chicken eggshells are disposed of in landfills, and Their decomposition produces ammonia, hydrogen sulfide and amines with significant odors. In addition to a foul smell and attracting mice, rats, flies and insects". Paradoxically, eggshells contain 94–97% calcium carbonate – a composition mirroring limestone but requiring no calcination when used as SCM, offering potential energy savings vs. clinker production.

Eggshell powder (ESP) has been widely studied as a partial cement replacement due to its high $CaCO_3$ content. Dezfouli. [10] demonstrated that 10% ESP incorporation improved early-age compressive strength, while higher levels (>20%) led to strength reduction due to dilution effects. Similarly, Paruthia et al. [11] reported that replacing up to 20% of the cement in concrete with eggshell powder increases the material's strength.

W. Soliman et al. [12] observed reduced bulk density and increased porosity with ESP substitution, which in turn decreased thermal conductivity, suggesting potential benefits for lightweight and insulating concretes. S. Sunardi et al. [13] highlighted that eggshells are composed of ~95% $CaCO_3$, making them comparable to limestone but without the need for calcination, thus offering significant CO_2 and energy savings. However, most of these studies were conducted in Asia or sub-Saharan Africa, and no systematic research has been reported on Moroccan ESP evaluated its potential as a supplementary cementitious material (SCM) despite the country generating ~40–50 kt/year of eggshell waste. Furthermore, limited attention has been given to thermal performance and long-term durability, leaving an important gap in knowledge.

This work addresses this gap by evaluating non-calcined Moroccan ESP, leveraging local waste streams and omitting energy-intensive processing steps. This study aims to: (1) Characterize Moroccan ESP's physicochemical properties by X-ray fluorescence and X-ray diffraction, and (2) Assess its impact on mortar density, water absorption, strength, and thermal conductivity/diffusivity at 10–30% cement replacement.

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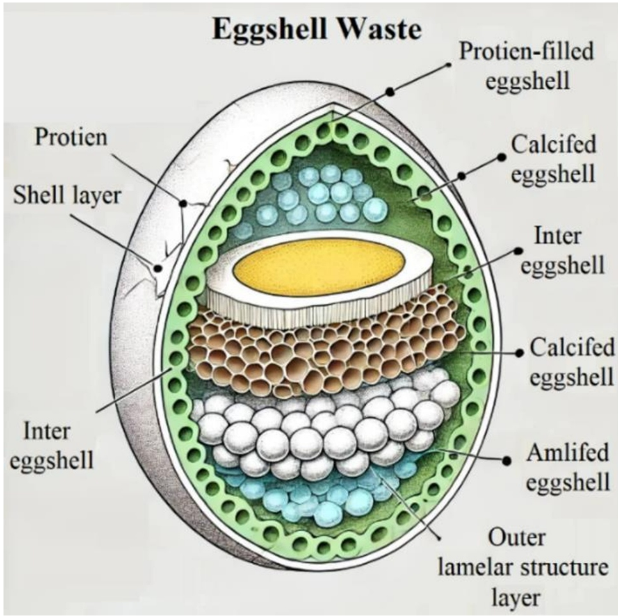

Fig 1. Multi-layered structure and organic-inorganic composition of eggshell waste [12].

2 Materials and sample preparation

2.1 Materials

The materials selection for this study was guided by two key objectives: (1) utilizing locally available resources to ensure practical applicability within the Moroccan construction sector, and (2) maintaining rigorous scientific standards for composite material development. The primary components consisted of ordinary Portland cement CPJ45 sourced from a regional Moroccan producer LafargeHolcim Maroc, Oujda plant [14] conforming to NM 10.1.004 standards [15]. crushed limestone aggregate (0/3 mm) with a fineness modulus of 2.3. The eggshell powder (ESP), was derived from post-consumer waste collected across Oujda's food service sector. X-ray fluorescence (XRF) analysis was carried out at the Oriental Center for Water Science and Technology (COSTE) [16]. The results confirmed its high-purity calcium carbonate composition (99.3 ± 0.8% CaO with trace SO_3/ K_2O/ Fe_2O_3 oxides), while X-ray diffraction (XRD) presented in Fig 2 revealed exclusive calcite phase crystallinity (R3c space group, dominant peak at 29.4° 2θ). The observed peak broadening in the XRD pattern is indicative of a biogenic calcite with low crystallite size, which is expected to enhance its reactivity compared to coarse-grained geological limestone.

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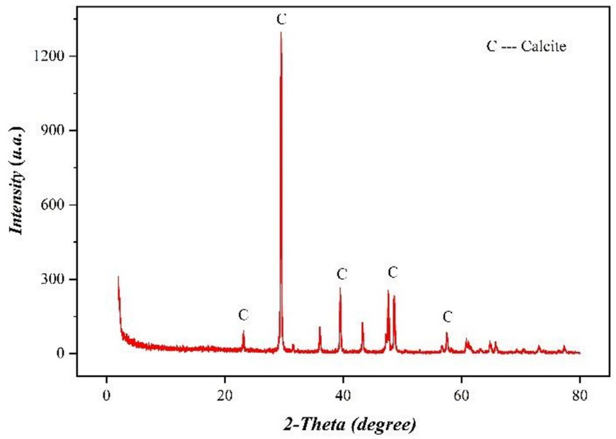

Fig. 2. XRD pattern of ESP.

Following material characterization, the eggshell processing protocol was implemented to transform raw waste into a standardized cement replacement material, as will be detailed in the following Section. The experimental methods for evaluating composite performance were then designed to assess both mechanical and thermal properties.

2.2 Sample preparation

Fig 3 illustrates the processing setup of ESP. Fresh eggshells from Moroccan food waste streams underwent manual cleaning with water to remove organic residues, followed by sun-drying (48 h) and oven-drying at 105°C (24 h) to achieve constant mass. Dry shells were mechanically crushed, then ground to achieve fine particulates. The powder was sieved through a 100-µm mesh to ensuring compatibility with cement particle sizes.

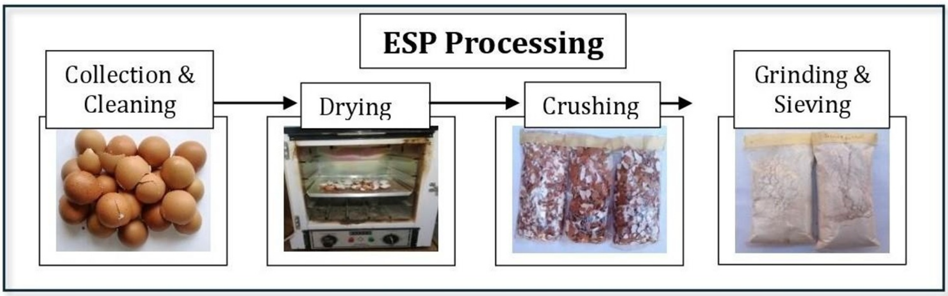

Fig 3. Process flow diagram of the eggshell treatment process.

For mortar formulations, ESP was pre-homogenized with cement using an electrical-blender (30 min at 50 rpm) to mitigate segregation risks, with substitution rates 10–30 wt% (see Table 1 and Fig 4). The specimens were prepared using a mix of binder (cement and ESP), sand and water, following by wet mixing, molding into cubic molds, and curing under room conditions.

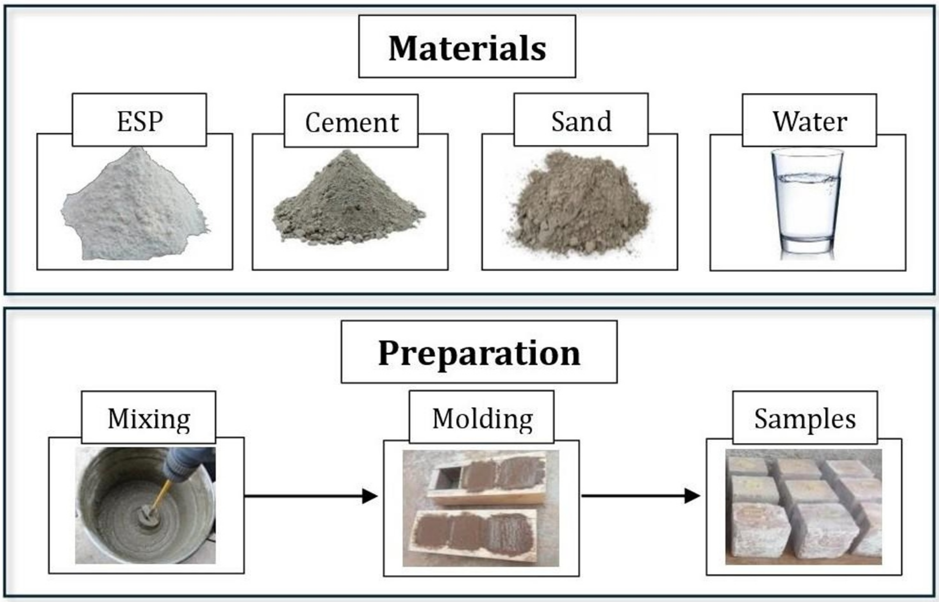

Fig 4. Sample preparation process of mortar specimens.

Table 1. Mix proportions for all mortar compositions (wt%).

Sample ID	Cement (%)	Eggshell (%)	Sand (%)
ES0	100	0	70
ES10	90	10	70
ES15	85	15	70
ES20	80	20	70
ES30	70	30	70

3 Methods

To evaluate the impact of ESP on cementitious composites, a multi-scale characterization protocol was employed combining standardized thermal, mechanical and durability tests as illustrated in Fig 5. Compressive strength testing was conducted on 50 mm cubic specimens cured for 7- and 90-days following ASTM C109 standards [17], using a 3000 kN capacity universal testing machine at a loading rate of 0.5 MPa/s. Water absorption was measured according to ASTM C642 [18] by first drying samples at 110°C to constant mass, then immersing them in water for 24 hours to determine both total absorption and capillary uptake.

Thermal properties were characterized using the Hot Disk method (ISO 22007-2 [19]) with a TPS 2200 instrument, employing transient plane source technique to measure thermal conductivity, and diffusivity. All tests were performed in triplicate to ensure statistical reliability. This methodology provided comprehensive insights into the material's mechanical durability and thermal performance while maintaining experimental rigor through standardized protocols.

Fig 5. Illustrates the experimental workflow, including mechanical testing and thermal analysis.

4 Results and discussion

4.1 Density and water absorption

Fig 6 illustrate that the incorporation of ESP as partial cement replacement significantly influenced the physical properties of the composites. As ESP content increased from 0% to 30%, water absorption rose progressively from 9.5% to 12.5%, representing a 31.6% increase. This trend can be attributed to two primary factors: (1) the dilution effect of reduced cement content, which decreases the formation of low-porosity C-S-H gel during hydration, and (2) the microstructural porosity introduced by ESP's irregular particle morphology. Simultaneously, bulk density exhibited a linear decrease from 2250 kg/m^3 (0% ESP) to 2050 kg/m^3 (30% ESP), an 8.9% reduction primarily due to ESP's lower intrinsic density compared to cement and the increased pore volume evidenced by water absorption trends. While these changes suggest excellent potential for lightweight applications, the increased water absorption at higher ESP dosages (particularly above 15%) may require additional protective measures for structures exposed to humid environments. The optimal 10-15% ESP range appears most promising, showing only a modest 7.4% increase in water absorption and 3.6% density reduction compared to conventional mortar, while still providing significant environmental benefits through cement replacement. These findings represent the first comprehensive dataset for non-calcined Moroccan ESP and demonstrate its viability as a sustainable construction material when properly dosed. The relationship between these bulk property changes and mechanical performance will be explored in the following section.

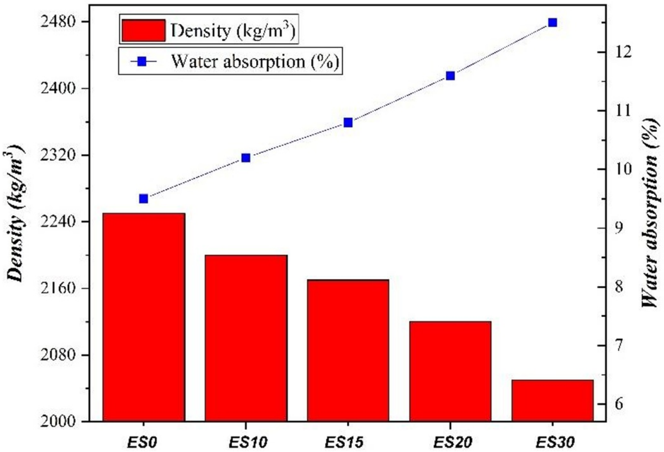

Fig 6. Physical properties: density and water absorption vs EPS content.

4.2 Compressive strength

The compressive strength evaluation revealed a systematic relationship between ESP content and mechanical resistance across curing periods (Fig 7). The reference mixture (0% ESP) developed expected strength values of 28 MPa at 7 days and 40 MPa at 90 days, serving as baseline for comparison. Incorporation of 10% ESP resulted in minimal strength reduction (7.5% at 7 days, 5% at 90 days), suggesting effective particle packing and possible nucleation effects. However, higher substitution rates demonstrated more significant impacts, with 30% ESP mixtures showing 28.6% and 25% strength decreases at 7 and 90 days respectively. This behavior follows three distinct phases: (1) Below 15% substitution, the strength reduction remains below 10%, indicating ESP particles primarily act as micro-fillers; (2) Between 15-20%, the decrease becomes more pronounced (17.5% at 90 days), revealing the cement dilution effect; (3) At 30% substitution, the combined effects of reduced cement content and increased porosity (as evidenced by water absorption results) lead to maximum strength loss. Importantly, all ESP-modified mixtures maintained adequate strength development trajectories, with even the 30% mixture achieving 30 MPa at 90 days - sufficient for many non-structural applications. These findings suggest that while ESP incorporation involves mechanical trade-offs, careful dosage selection (particularly in the 10-15% range) can maintain structural viability while delivering environmental benefits through cement reduction. The thermal performance characteristics of these mixtures, which may offset some mechanical limitations, are examined in the following section.

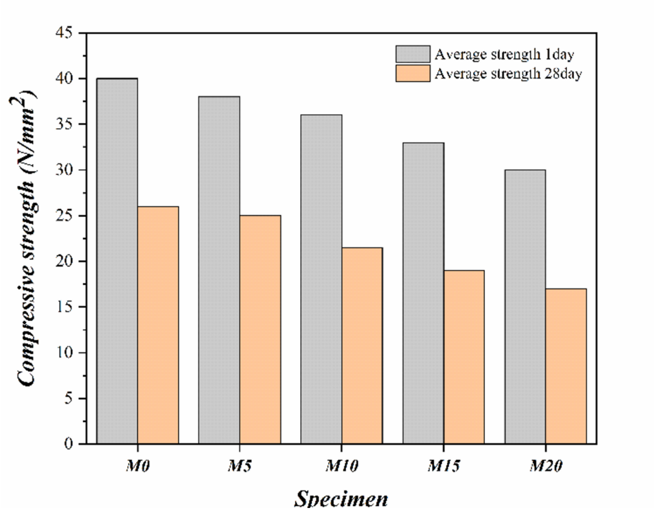

Fig 7. Compressive strength.

4.3 Thermal properties

The thermal characterization of ESP-modified composites revealed significant improvements in insulation performance while maintaining adequate thermal mass (Table 2). Thermal conductivity decreased progressively from 1.15 W/m·K for the control mix to 0.82 W/m·K at 30% ESP substitution, representing a 24.6% enhancement in insulation capacity. This improvement stems from two complementary mechanisms: (1) the intrinsic low thermal conductivity of calcium carbonate (2.7 W/m·K) compared to cement phases (3.2 W/m·K), and (2) the increased microporosity evidenced by water absorption tests, which introduces insulating air voids (0.026 W/m·K). Thermal diffusivity followed a similar trend, decreasing from 0.52 to 0.35 mm²/s, while specific heat capacity increased by 12.3%, indicating these materials would provide both better insulation and maintained thermal energy storage capacity - a crucial combination for passive building temperature regulation. The 15% ESP formulation emerged as particularly promising, offering a 15.4% reduction in thermal conductivity while limiting the compressive strength decrease to 10%, making it suitable for structural applications where improved thermal performance is desired. Higher ESP contents (20-30%) achieved more dramatic thermal improvements (up to 24.6%) but with greater mechanical trade-offs, suggesting their best application might be in non-load-bearing insulation elements. These results position ESP as a unique multifunctional additive that can simultaneously address both structural and energy efficiency requirements in sustainable construction, particularly relevant for Morocco's climate where both thermal mass and insulation are important for building comfort.

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Table 2. Thermal conductivity, diffusivity, and Specific heat capacity vs ESP content.

Specimen	Thermal conductivity (W/m·K)	Thermal diffusivity (mm^2/s)	Specific heat capacity (J/kg·K)
ES10	1.15	0.52	0.85
ES15	1.05	0.47	0.92
ES20	0.98	0.44	0.96
ES30	0.90	0.39	0.99
ES10	0.82	0.35	1.03

5 Conclusion

This study demonstrates that eggshell powder (ESP) derived from Moroccan food waste can effectively serve as a sustainable partial replacement for cement in construction materials. The experimental results reveal a clear trade-off between mechanical performance and thermal properties as ESP content increases. At optimal substitution levels of 10-15%, the composites maintain over 90% of the reference compressive strength (36-38 MPa at 90 days) while improving thermal insulation by 15%. Higher ESP dosages (20-30%) show more significant thermal benefits but require careful consideration for structural applications due to greater strength reductions.

From an environmental perspective, this research presents a practical solution for valorizing Morocco's estimated 150,000 tons of annual eggshell waste while reducing the construction sector's carbon footprint. Each 15% cement replacement with ESP potentially saves approximately 120 kg of CO_2 emissions per ton of cement produced. The improved thermal properties, including reduced conductivity (down to 1.32 W/m·K) and increased heat capacity, make ESP-modified composites particularly suitable for energy-efficient building applications in Morocco's climate.

This research establishes ESP as a promising, locally available material that aligns with Morocco's circular economy goals and sustainable development priorities in the construction sector. By transforming an abundant waste stream into a valuable construction material, this approach offers simultaneous environmental, economic, and technical benefits for Morocco's building industry.

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