EPJ Web of Conferences **371**, 01014 (2026) https://doi.org/10.1051/epjconf/202637101014
AMT'2026

Development of eco-efficient earth bricks incorporating mussel shells for enhanced thermal performance

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Abstract. As part of the development of sustainable and high-performance construction materials aimed at reducing greenhouse gas emissions while improving energy efficiency, this study focuses on the incorporation of mussel shells, a by-product, for the stabilization of compressed earth bricks (CEBs). The main goal is to assess how the addition of mussel shells influences the thermal, thermodynamic, and mechanical behavior of these bricks. Different formulations were tested with incorporation rates of 5%, 10%, 15%, and 20% mussel shells. The results show that the incorporation of mussel shells enhances the thermal insulation performance of buildings by reducing heat transfer while increasing heat storage capacity. Dynamic thermal analysis revealed the existence of an optimal brick thickness ensuring an effective thermal phase shift. The novelty of this study resides in applying dynamic thermal analysis based on the NF EN ISO 13786 standard to compressed earth bricks stabilized with mussel shells an approach not previously reported in the literature. Regarding mechanical performance, the incorporation of mussel shells was found to strengthen the structural resistance of compressed earth bricks. Overall, these results highlight the potential of this approach as a viable and sustainable solution for the construction sector, while simultaneously valorizing a waste product from the aquaculture industry.

Keywords: Energy efficiency, buildings, Earth Bricks, Mussel Shells, Thermal Properties, Dynamic Thermal Characteristics, Compressive Strength.

1 Introduction

In the context of the energy transition and the fight against climate change, research is increasingly focusing on optimizing construction materials to improve the energy efficiency of buildings. This approach represents a passive solution that reduces the need for heating and cooling. Compressed earth bricks (CEBs) are known for their low environmental impact, availability, and favorable thermal and hygroscopic properties, making them more efficient than concrete and fired bricks [1]. However, they have limitations in terms of mechanical properties and durability.

To address these shortcomings, several studies have explored the integration of bio-based materials and industrial by-products to enhance the performance of CEBs. Some of these

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studies focus on the addition of natural fibers. In this perspective, Oubani et al. [2] demonstrated that incorporating Alfa fibers into CEBs reduces mechanical strength but improves thermal properties and resistance to erosion. Similarly, Sadouri et al. [3] showed that adding Juncus fibers to CEBs with varying cement contents enhances their durability, thermal insulation, and ultrasonic pulse velocity, despite a slight decrease in mechanical strength.

Other studies concentrate on stabilizing CEBs using by-products, an approach that helps reduce industrial waste while promoting its valorization in the construction sector. In this context, El Hammouti et al. [4] used olive pomace to reinforce CEBs, resulting in an environmentally friendly thermal insulation material suitable for sustainable construction. Likewise, Umar et al. [5] revealed that stabilizing clay soils with marble powder waste as an alternative binder improves the mechanical properties of the material, making it more robust, stable, and resistant to compressive and tensile forces. This effect becomes more pronounced over time, particularly after 28 days of curing. Their results show an improvement in compressive and flexural strength for moderate replacement rates, while higher proportions increase porosity and water absorption, leading to a decrease in strength.

In addition, other research suggests that the incorporation of certain by-products can also enhance the mechanical performance of CEBs. For example, Lejano et al. [6] showed that adding 10% green mussel shells and 0.75% pig hair improves compressive strength, flexural strength, and durability. Similarly, Sathiparan [7] and Khalil et al. [8] investigated the effect of adding peanut and mussel shells to CEBs, revealing improvements in thermal performance and insulation, despite a slight reduction in mechanical strength.

From this brief literature review, it can be concluded that stabilizing compressed earth bricks with eco-friendly materials represents a promising approach to reduce greenhouse gas emissions while improving the energy efficiency of buildings. This research aims to stabilize CEBs with mussel shells and to characterize their thermal, dynamic thermal, and mechanical properties. The main difference between this study and previous works lies in the characterization of the overall thermal behavior, including dynamic thermal properties based on the NF EN ISO 13786 standard, an area that remains underexplored and could open new perspectives for the development of smart construction materials. To this end, a series of stabilized earth mixtures were developed, gradually incorporating 5%, 10%, 15%, and 20% mussel shells. The objective is to determine whether this approach can produce a material that is high performing, durable, and well suited to the requirements of energy efficiency and sustainable development.

2 Experimental details

The base material used in this study is raw earth collected from the Marrakech region of Morocco. X-ray diffraction (XRD) and X-ray fluorescence (XRF) analyses were carried out to identify its mineralogical and chemical composition. The results confirm that the soil is rich in silicates and aluminosilicates, mainly composed of quartz, albite, and goethite, with traces of kaolinite. This composition influences the plasticity of the material, with a plasticity index (PI) of about 14%, indicating moderate plastic behavior. The bulk and absolute densities are approximately 1962.92 kg/m³ and 2696 kg/m³, respectively [10].

In addition, scanning electron microscopy (SEM) was used to observe the microstructure of the soil (**Fig.1.a**). The SEM images reveal a heterogeneous and fine-grained texture with visible micropores, confirming its mineralogical heterogeneity and compact structure.

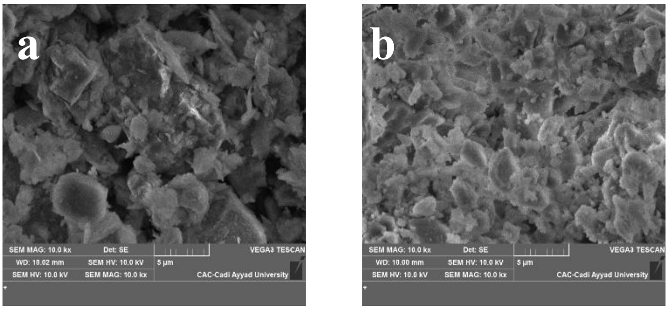


Fig.1. SEM images of, (a) in the soil and (b) in the mussel shells

The additive consists of mussel shells collected from the Agadir region. XRF analysis indicates a high CaO content, confirming their predominantly calcareous composition. XRD shows that the shells are mainly composed of aragonite [10]. SEM observations (**Fig.1b)** reveal a compact lamellar structure with low porosity, suggesting a limited capacity for moisture interaction.

Before shaping the samples for thermal and mechanical measurements (weighing, water addition, mixing, and compaction), the soil mussel shell composite was initially dried at approximately 105 °C for 24 hours. Subsequently, precise amounts of the dried composite powder were prepared: 20 g for thermal conductivity measurements and 80 g for compressive strength testing. These portions were then mixed with the previously determined optimum water content in order to achieve maximum dry density. The mixtures were prepared in five series: one based on pure soil and four others incorporating mussel shells at contents of 5%, 10%, 15%, and 20%. For each formulation, several specimens were prepared following the same preparation protocol in order to ensure reproducibility. After preparation and compaction, the specimens were stored under laboratory conditions for one week, then oven dried at 105 °C for 24 hours prior to thermal and mechanical testing. Details of the experimental procedure, including sample preparation and the equipment used for thermal and mechanical testing, are provided in our previous works [2,10].

3 Experimental results and discussion

3.1 Effect of mussel shell addition on thermal properties

As it is seen from **Fig. 2a**, the addition of mussel shells to the soil involves a monotonous increase in the mixture density (ρ) due to the decrease in porosity (the shells fill the gaps and reduce porosity). **Fig. 2b** shows that the soil reinforced by the mussel shells leads to a continuous decrease in the thermal conductivity (λ) of the mixture, from 0.479 (W/m.K) for pure soil to 0.465 (W/m.K) for the mixture containing 20% mussel shells. This finding confirms the results found previously and prove that the mixture (λ) is significantly lower than that of raw earth [9] These results are also consistent with those of Khalil et al. [8], who found that reinforcing compressed earth bricks with mussel shells is an effective method to improve thermal insulation by reducing the thermal conductivity of the bricks. Another work related to Garcia et al. [9] show that mussel shells should be considered as an insulating material due to their low (λ). Simultaneously, the heat capacity (Cp) shows a slight increase, rising from 402.042 (J/kg.K) to 482.930 (J/kg.K) with increasing mussel shells content up to 20% (**Fig. 2c**).

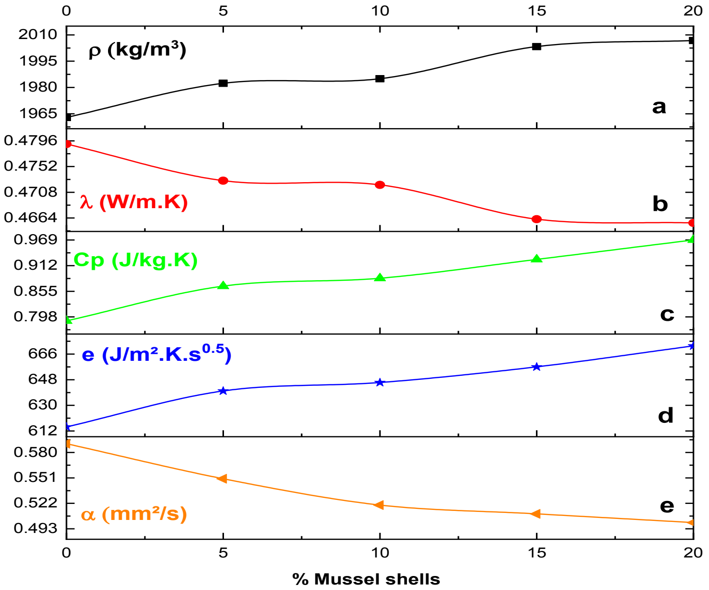


Fig. 2. Variation of (a) dry density, (b) thermal conductivity, (c) heat capacity, (d) thermal effusivity and (e) thermal diffusivity as a function of mussel shell content.

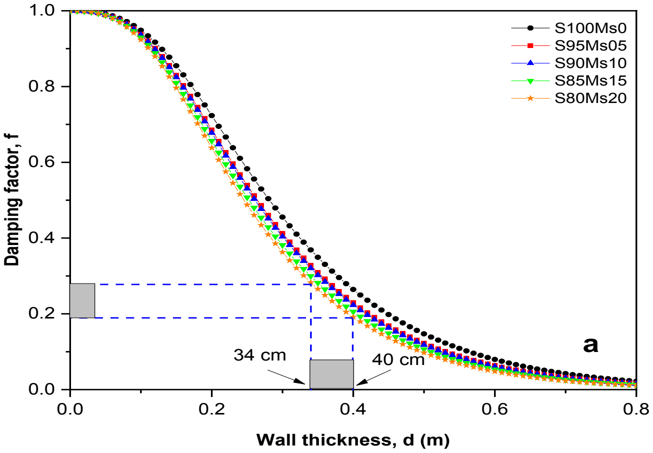
These values suggest that the mussel shells, having a higher (Cp) than the soil, contribute to absorbing and storing more heat. Similar results were obtained by Maglad et al. [11], who found that the specific heat value increases with the amount of mussel shell used and that the ultrafine particles derived from mussel shells could be responsible for these high Cp values. However, although (λ) decreases, the results reveal an increase in the thermal effusivity (e) of the samples with the increase mussel shell content (**Fig. 2d**), rising from 614.864 (J/m².K.$s^{0.5}$) for pure soil to 671.707 (J/m².K.$s^{0.5}$) with 20% mussel shells amount. This signifies the dominance of the increase in density (ρ) and specific heat capacity (Cp). Even though (λ) decreases, it does not compensate for the increase in ρ·Cp, leading to an overall increase in (e). Furthermore, the sumultanous increase in ρ·Cp and decrease in (λ) results in a decrease in thermal diffusivity (α), which drops from 0.59 (mm²/s) for pure soil to 0.50 (mm²/s) with 20% mussel shells amount (**Fig. 2e**); indicating that the material takes longer to respond to temperature variations. It stores heat more efficiently while reducing its internal propagation speed.

3.2 Effect of mussel shell addition on dynamic thermal properties

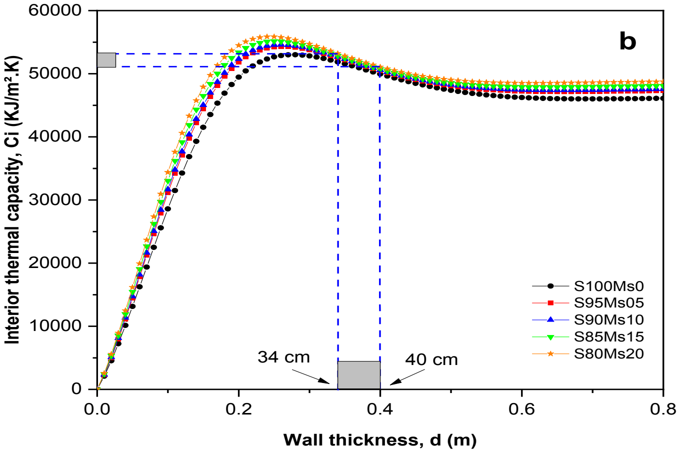
In this section, we used the experimental values of (λ) and (Cp) to analyze the dynamic thermal behavior of the samples. This factor is particularly useful in evaluating the heating and cooling needs of buildings thereby helping to evaluate the contribution of the studied materials to overall energy efficiency.

Dynamic thermal behavior describes how a building element responds to fluctuations in the surrounding thermal conditions. Specifically, the material surfaces are subjected to sinusoidal temperature or heat flux variations, allowing for the analysis of its response under variable conditions. The assessment of these parameters was performed in compliance with the NF EN ISO 13786 standard [12]. Assuming constant thermal properties for a homogeneous and isotropic layer, as well as unidimensional heat flux, the approach adopted is based on the quadripolar method. This method involves establishing the thermal transfer matrix (Z), which relates the complex amplitudes of temperature and heat flux on one side of the material to those on the other side. From this matrix, we calculated four key indicators: the damping factor (*f*), the interior thermal capacity (Ci), the thermal resistance (Rth) and the phase shift (ϕ).

Fig. 3a shows that the (*f*), which reflects the ability of the wall to mitigate external temperature variations, decreases with increasing thickness for all the studied formulations. Moreover, the addition of mussel shells to pure earth involves a reduction of (*f*) and thereafter improves thermal insulation by enhancing the temperature difference between the two sides of the material.



As can be seen from **Fig. 3b**, the surface heat capacity (Ci) of the earth and shell formulations increases rapidly with the wall thickness (d), reaching a maximum. Beyond this threshold depending on (d), (Ci) slightly decreases and tends to stabilize. For a fixed value of (d), we can deduce that the material composition strongly influences (Ci): higher the mussel shell content, greater the interior heat capacity. This means that reinforcing compressed earth bricks can store more heat, promoting thermal inertia and improving indoor thermal comfort by reducing temperature fluctuations.



The evolution of (Rth) as a function of the wall thickness is presented in **Fig. 3c**. As shown in this figure, (Rth) increases linearly with the wall thickness. Although this increase, (Rth) remains below the values required by thermal regulations in Morocco for reasonable thicknesses. In the other hand, the addition of mussel shells reduces thermal conductivity of mixed material and consequently enhances (Rth).

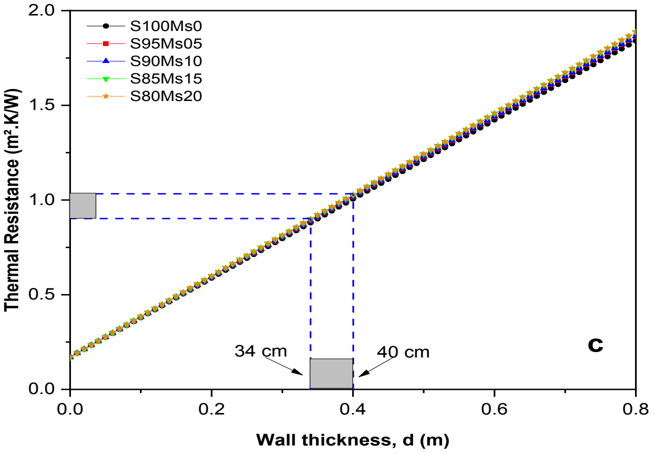


Fig. 3d shows the time lag of the composition containing 20% mussel shells. This percentage was selected because it exhibits the best thermal performance among all tested formulations: the lowest (λ), the highest (Ci), the lowest (f), and the highest (Rth). The ideal thickness to achieve the day/night phase shift, ranging from 10 hours to 12 hours, required for thermal comfort, is between 34 cm and 40 cm (as seen in the insets of Fig. 3d). The corresponding ranges of (f), (Ci) and (Rth) are approximately [0.27 - 0.19], [53.27 (kJ/m²·K) - 51.08 (kJ/m²·K)],[0.9 (m²·K/W) - 1.03 (m²·K/W)]. The other formulations are not presented here as the differences in terms of thickness are not significant.

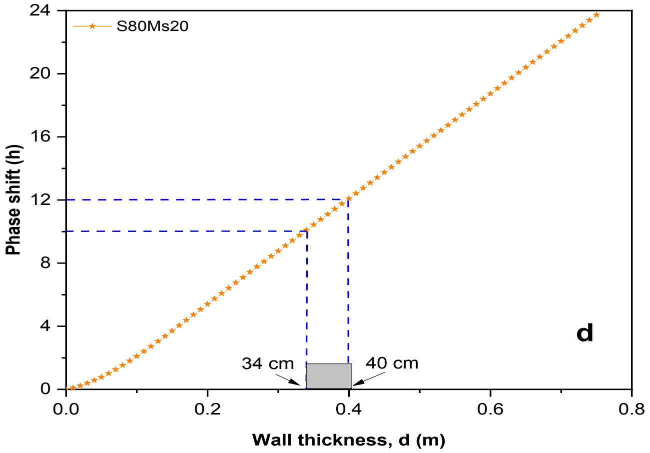


Fig. 3. Evolution of: (a) damping factor, (b) interior thermal capacity, (c) thermal resistance and (d) phase shift as a function of wall thickness for different mussel shell contents, in conduction-convection-radiation mode.

Table 1 presents the dynamic thermal parameters evaluated at a fixed wall thickness of 36 cm. The comparison between the reference material without mussel shells and the formulation containing 20% mussel shells highlights a clear improvement in dynamic thermal performance. The incorporation of mussel shells leads to a reduction in the damping factor and an increase in interior thermal capacity and thermal resistance, indicating an enhancement of thermal inertia and overall energy efficiency.

Table 1. Comparison of dynamic thermal parameters (f, Ci, Rth, ϕ) of stabilized compressed earth bricks with 0% and 20% mussel shells at a fixed wall thickness of 36 cm

	f	***Ci (kJ/m²·K)***	***Rth (m²·K/W)***	***Φ (h)***
S100Ms0	0.330	51253.289	0.921	9.337
S80Ms20	0.248	52445.565	0.943	10.763

3.3 Effect of mussel shell addition on mechanical properties

Fig. 4 shows that the incorporation of mussel shells to the soil increases the maximum compressive strength (R_{cmax}), rising from 3.699 MPa for pure soil to 3.993 MPa for a mixture with 20% mussel shells. This improvement can be explained by two mechanisms. First, densification: there is an increase in dry density (ρ) with the increase in shell content (**Fig. 2a**), which improves the compressive strength (R_{cmax}) of the soil because a denser material has fewer voids and thus fewer weak zones. Such explanation was reported in reference [13]. On the other hand, the mussel shell particles being well compacted with the soil ones, contribute to a better redistribution of the applied stresses. Second, mussel shells are primarily composed of calcium carbonate.

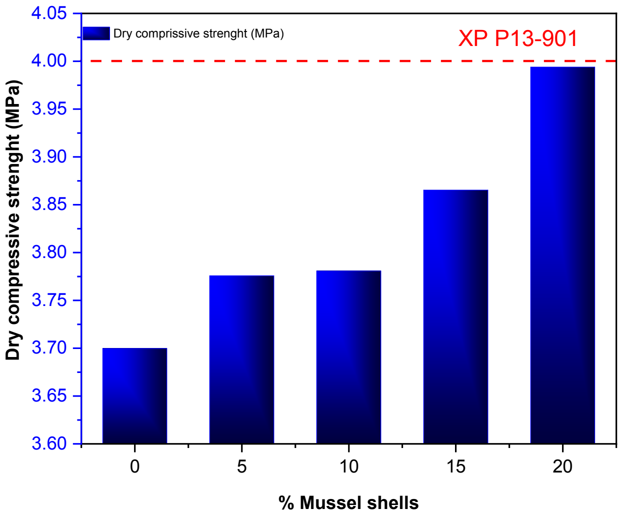


Fig. 4. Variation of dry density and dry compressive strength as a function of mussel shell content.

Their incorporation into the material promotes better compaction by reducing void spaces and subsequently strengthening the soil structure. In relation to this phenomenon, Freitas et al. [14] confirm that micronized mussel shells are more effective than traditional $CaCO_3$

sources in reducing the porosity of concrete and mortar beyond 28 days. Thus, the use of fine aggregates improves mechanical properties. But according to the French standard XP P13-901 [15], all the studied formulations exhibit a dry compressive strength higher than the minimum required threshold of 2 MPa. However, this strength remains slightly below the 4 MPa threshold required for using the blocks as load-bearing elements in the construction of two-storey buildings, including the formulation containing 20% mussel shells, which reaches 3.993 MPa but still falls outside the range defined by the standard. Therefore, it is recommended to limit their use to interior partitions or small-scale constructions that do not require high mechanical strength.

4 Conclusion

The use of mussel shells to stabilize compressed earth bricks not only allows for the valorization of aquaculture waste as a by-product but also promotes the development of eco-friendly building materials. This approach represents a promising solution for sustainable and high-performance construction, while enhancing energy efficiency.

The results obtained allow us to draw the following conclusions:

- The addition of mussel shells improves thermal performance by reducing (λ) and (α), while increasing (Cp) and (e). This makes the material more thermally insulating, with an improved ability to store heat and slow down its internal propagation.
- The thermal results were further analyzed to assess the dynamic thermal behavior. It was found that the (f) decreases, while the (Ci) and (R_{th}) increase with higher mussel shell content. The optimal wall thickness for the formulation containing 20% mussel shells lies between 34 and 40 cm. These results confirm the positive impact of mussel shell incorporation on the thermal performance of the material, by enabling better regulation of indoor temperature fluctuations and contributing to thermal comfort.
- Stabilizing compressed earth bricks with mussel shells increases mechanical strength up to 3.993 MPa, making the material more compact and reducing porosity, thus strengthening the soil structure. Despite this improvement, the blocks remain suitable for non-load-bearing applications, in compliance with the requirements of standard XP P13-901.

Overall, it can be concluded that the incorporation of mussel shells enhances the thermal insulation of buildings while improving the mechanical properties of compressed earth bricks. These results meet the performance requirements for sustainable and energy efficient construction materials. In the long term, the use of mussel shell waste contributes to reducing the environmental footprint of construction materials by limiting the consumption of natural resources and promoting waste recycling. This approach supports the durability of earthen materials while aligning with circular economy and sustainable development principles.

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