Energy Evaluation of an Innovative Passive Building Using a Red Clay, Limestone, and Lime Composite for Mediterranean Regions

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Abstract. Mediterranean housing is increasingly shifting from a heating- to a cooling- dominated regime, making thermal comfort and energy efficiency central design challenges. This study assesses a passive multi-story envelope based on a red clay–limestone–lime composite. Thermophysical properties (ρ = 1800 kg/m³, c = 950 J·kg⁻¹·K⁻¹, and $\lambda \approx$ 0.70 W·m⁻¹·K⁻¹) were implemented in COMSOL Multiphysics 6.2 to run 1-D transient heat-transfer simulations of a layered wall over representative 72 h summer and winter temperature sequences. Relative to a cement-based reference wall, the composite halves daily indoor temperature swings (peaks reduced from about ±3 °C to around ±1.5 °C), increases phase shift, and reduces HVAC energy required to maintain setpoints (25 °C in summer and 20 °C in winter). For a 0.20 m core, cooling energy over 72 h decreases by 54.9% (32.136 to 14.506 kWh) and heating energy by 48.0% (52.496 to 27.289 kWh); increasing thickness to 0.30 m yields reductions of up to 58.8% (cooling) and 47.0% (heating). A conductivity sweep indicates best performance for $\lambda \approx$ 0.60–0.70 W·m⁻¹·K⁻¹.
These results demonstrate the potential of locally sourced mineral composites to support passive-building strategies and Near Zero Energy Building (NZEB) objectives in Mediterranean climates. By combining traditional resources (red clay, limestone, and lime) with modern passive design principles, the proposed wall system offers a practical pathway to improved thermal stability, reduced peak loads, and enhanced indoor comfort.

Keywords: Mediterranean climate; passive building; thermal inertia; lime-based composites; NZEB; red clay; limestone; lime wall.

1. Introduction

As summers intensify across the Mediterranean, residential buildings are progressively shifting from heating - to cooling - dominated operation. Scenario-based studies consistently show that, without envelope adaptation, cooling demand increases and overheating hours accumulate even under moderate weather conditions. In this context, design priorities extend beyond winter U-value targets toward strategies that damp diurnal loads -peak shaving, phase shift, and free-running thermal stability- supported by appropriate ventilation and setpoint management (1-3).

A robust response in Mediterranean climates is to leverage high-inertia, vapor-open wall systems that attenuate outdoor day–night forcing while maintaining breathability. Full-scale test-cell and building-scale investigations of earthen walls in Mediterranean contexts report favorable thermal buffering and smoothing of daily temperature cycles when material properties and detailing are well controlled (4-6). In parallel, lime-based binders offer additional CO_2-abatement pathways through lower process energy, local manufacture, and in-service carbonation, provided that specifications and workmanship follow best practice (7-9).

Recent Mediterranean case studies of bio-based lime composites (e.g., hemp–lime blocks and renders) further underline the value of moisture buffering, moderate conductivity, and circular feedstocks for comfort and durability in warm conditions. Monitored buildings in northern and southern Italy, for example, report humidity regulation and potential operational energy reductions when vapor openness is preserved (10-12).

While active measures (e.g., building-integrated photovoltaics) can substantially improve performance, there is broad consensus that passive design should be addressed first—building form and orientation, solar control, night ventilation, and thermally engaged mass. Parametric studies on Mediterranean dwellings show that orientation and envelope strategies materially influence final energy balances; once the passive base is optimised, active solar systems provide additional gains (13, 14).

Objective and contribution. Building on this background, the present study evaluates a red clay–limestone–lime composite as the massive core of a layered wall for passive multi-storey buildings in Mediterranean climates. Using

COMSOL Multiphysics 6.2, we simulate 72 h summer and winter transients and perform parametric sweeps on core thickness and thermal conductivity, benchmarking against a cement reference. We quantify (i) free-running indoor stability (amplitude and phase shift) and (ii) HVAC power and 72 h energy required to hold comfort setpoints and interpret results with respect to Mediterranean overheating risk and NZEB aims to provide practical guidance for envelope sizing and material selection (2, 13, 15).

2. Materials

2.1. Composite concept and wall build-up

The proposed envelope uses a red clay–limestone–lime composite as a massive core, finished on both sides with lime-based renders to keep the assembly vapor-open and compatible with mineral substrates.

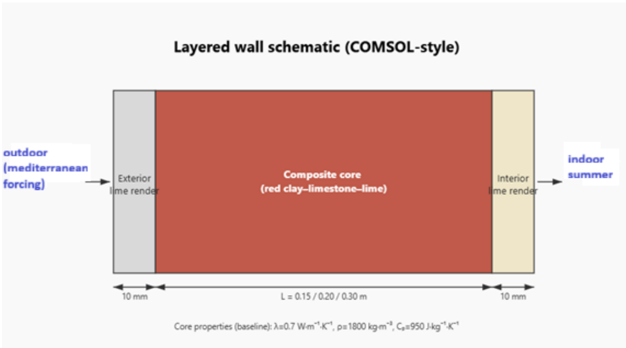

Fig. 1. Layered wall schematic (thicknesses and materials).

This configuration leverages thermal inertia to shave diurnal peaks under Mediterranean forcing (24-h cycles) while preserving moisture buffering and repairability typical of lime systems. Full-scale Mediterranean test cells with earthen/mass walls report strong attenuation of outdoor temperature amplitude and quasi-steady inner surface temperatures, supporting the role of mass in free-running stability (1-3).

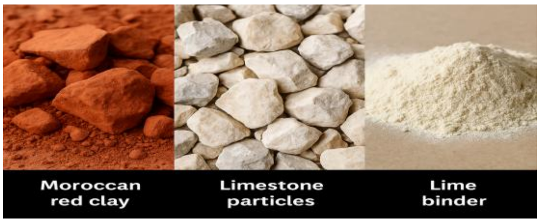

Fig. 2. Local constituents of the composite (red clay, limestone, lime).

For benchmarking, a cement-based core of similar thickness is modeled as a reference wall. Lime renders are preferred to cementitious finishes because they maintain breathability and align with low-carbon maintenance practices for mineral envelopes (4-6).

2.2. Constituents and rationale

Core (red clay–limestone–lime): mineral composite targeting high volumetric heat capacity (ρ·Cp) with moderate conductivity so the mass remains thermally coupled to indoor air over a diurnal cycle. Mediterranean cubicle studies show amplitude reduction and phase shift for mass walls under summer/winter sequences.

Exterior/interior lime renders: ensure vapor openness, salt-tolerant durability, and in-service carbonation potential key levers for CO_2 abatement versus Portland-cement renders when detailing avoids moisture traps(4-6).

Optional bio-based modifiers (context): Mediterranean hemp–lime case studies demonstrate low λ and hygroscopic buffering that support comfort and energy use; this motivates the breathable finishes and target ranges we adopt (7-10).

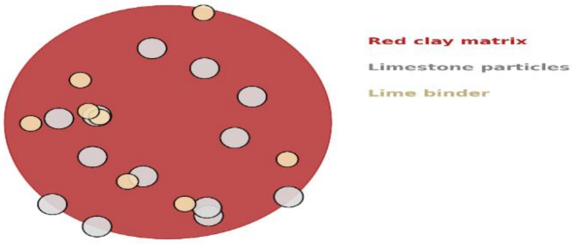

Fig. 3. Conceptual microstructure of the composite.

2.3. Target thermophysical properties and ranges

Material	Density (kg/m³)	Specific heat c (J·kg⁻¹·K⁻¹)	Thermal conductivity λ (W·m⁻¹·K⁻¹)	Compressive strength (MPa)
Composite (red clay-limestone-lime)	1800	950	0.70	3—5
Cement based reference	2200	880	1.4	25

Table 1. Material properties used in the model (composite vs. cement).

Table 1 reports the properties used in the model—thickness, thermal conductivity λ, density ρ, and specific heat capacity c—for the composite and the cement reference. For lime–sand mortars, $\lambda \approx 0.60\ W\cdot m^{-1}\cdot K^{-1}$ is consistent with reported needle-probe characterizations, and PCM-modified lime renders can further reduce λ while increasing apparent heat capacity when a thermal-storage layer is pursued (17). Massive earth/lime systems at wall scale exhibit strong amplitude attenuation of outdoor cycles, supporting the selected ρ·c and moderate-λ regime for Mediterranean diurnal forcing.

2.4. Hygrothermal behaviour (moisture buffering)

Lime and bio-mineral composites are hygroscopic and breathable, stabilizing indoor RH and limiting microbial growth when properly detailed. In monitored Mediterranean buildings, hemp–lime showed humidity regulation and energy reductions relative to lightweight mineral alternatives, linking moisture buffering to lower sensible cooling demand (7-9, 11). Where hygrothermal layers are enhanced (e.g., PCM-modified lime mortars), standardized tests exist for capillary uptake, salt crystallization, and freeze–thaw, along with thermal characterization protocols; our study remains sensible-heat focused, but these methods frame future hygrothermal coupling (12-15).

2.5. Transient simulations and derived metrics

Transient simulations were run in COMSOL Multiphysics 6.2 for 72-h summer and winter design sequences. We compute (i) free-running indoor stability (amplitude, phase shift) and (ii) HVAC power and 72-h energy to hold setpoints. We also report derived metrics R_KW (effective thermal resistance in kW^{-1} units over the active area) and τ_h (dominant time constant in hours) used later to interpret parametric trends(4-6, 16).

2.6. Parametric plans (what is swept and why)

Two parametric axes are explored:

- Thickness sweep (L = 0.15, 0.20, 0.30 m) for both composite and cement baseline to observe mass-coupling effects on loads and stability.
- Composite conductivity variants (λ = 0.6, 0.7, 0.8 $W \cdot m^{-1} \cdot K^{-1}$) at fixed L = 0.20 m, to bound uncertainty and tune density/porosity targets.

3. Methods

3.1 Model scope and wall assembly

We model a multilayer wall (exterior → interior): lime–sand render (~15 mm), red clay–limestone–lime composite core (L = 0.15–0.30 m), and earthen/lime render (~20 mm). The cement reference wall replaces the core with a cement-based material of identical thickness. Properties (thickness *e*, conductivity *λ*, density *ρ*, specific heat *C*) are those given in Table 2 (Section 2)(1-3).

Parameter	Value	Unit
Wall area A	10	m²
Base thickness L	0.20	m
Thickness sweep	0.15; 0.20; 0.30	m
Time step Δt	60	s
Simulation horizon	72	h

Table 2. Geometry and numerics (A, L, Δt, horizon, etc.).

The wall is sized so that its mass stays thermally engaged over the diurnal cycle typical of Mediterranean climates.

Rationale for the 72h simulation window. A 72h horizon (three consecutive diurnal cycles) captures the transient response, phase shift, and peak-shaving behavior of high-inertia walls under Mediterranean day-night forcing, while reducing sensitivity to initial conditions and maintaining a computationally tractable setup for parametric sweeps.

3.2 Boundary conditions: Mediterranean transients

Two 72 h transients are prescribed:

- Summer: outdoor air Te(t) ≈ 32 ± 6 °C with early-afternoon peaks.
- Convective heat-transfer coefficients were set to he = 20 $W \cdot m^{-2} \cdot K^{-1}$ (exterior) and hi = 8 $W \cdot m^{-2} \cdot K^{-1}$ (interior).

These sequences capture the strong day–night amplitude that drives summer cooling loads and tests free-float stability (24, 25).

Season	Outdoor T mean (°C)	Amplitude (°C)	Indoor setpoint (°C)	Duration (h)
Summer	32.0	6.0	25.0	72
Winter	10.0	4.0	20.0	72

Table 3. Climate and setpoints (72-h sequences).

3.3 Physics and solver

We solved 1-D transient heat conduction (COMSOL Multiphysics 6.2, Heat Transfer in Solids) through the multilayer slab for 72 h, with convection at both surfaces. Outputs were:

Free-float: interior surface temperature $Tsi(t)$Tsi(t) (no HVAC);

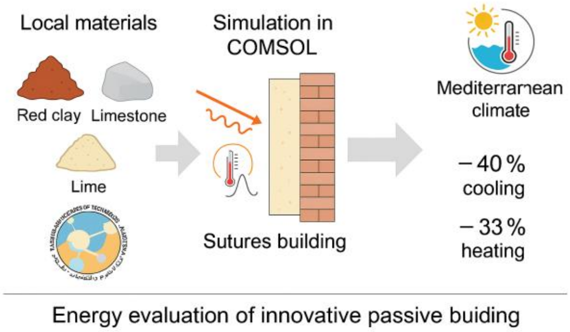

Fig. 4. Simulation workflow.

Controlled: interior surface clamped to 25 °C (summer) / 20 °C (winter); the interior convective heat flux:

$$qi(t)=hi\,(Tsi-Tair,\,i);$$

served as an HVAC power proxy, integrated over 72 h for energy (Wh.m⁻²). Meshing was refined at interfaces; time stepping was adaptive around peaks.

3.4 Performance metrics

We report: (i) indoor amplitude (peak-to-trough) and phase shift (lag vs. outdoor peak) under free-float; (ii) 72 h energy for cooling/heating under controlled runs; and (iii) peak HVAC power. These metrics track both comfort and energy performance in line with Mediterranean overheating-risk methodology (17, 18).

3.5 Parametric plan

Thickness sweep: Lcore = 0.15, 0.20, 0.30 m at fixed λcore = 0.70 $W\cdot m^{-1}\cdot K^{-1}$ (Table 4).

Thickness L (m)	Summer Cement (kWh)	Summer Composite (kWh)	Δ vs cement (%)	Winter Cement (kWh)	Winter Composite (kWh)	Δ vs cement (%)
0.15	45.138	21.255	52.9 %	68.468	35.110	48.7 %
0.20	32.136	14.506	54.9 %	52.496	27.289	48.0 %
0.30	18.504	7.616	58.8 %	36.944	19.563	47.0 %

Table 4. Conductivity sweep: λcore = 0.60, 0.70, 0.80 $W\cdot m^{-1}\cdot K^{-1}$ at fixed Lcore = 0.20 m (Table 5).

at fixed Lcore=0.20 m.

λ composite ($W\cdot m^{-1}\cdot K^{-1}$)	0.60	0.70	0.80
Summer composite (kWh)	11.973	14.506	17.061
Cement (kWh)	32.136	32.136	32.136
Δ vs cement (%)	62.7%	54.9%	46.9%
Winter composite (kWh)	23.698	27.289	30.866
Cement (kWh)	52.496	52.496	52.496
Δ vs cement (%)	54.9%	48.0%	41.2%

Table 5. Conductivity sweep (λcore = 0.60, 0.70, 0.80 $W\cdot m^{-1}\cdot K^{-1}$ & Lcore = 0.20 m): 72h energy & dynamic metrics.

Each case is run for summer and winter; post-processing aggregates 72h energy and peak power.

3.6 Hygrothermal and durability context (for interpretation)

Although this study focuses on sensible heat, moisture state can shift effective *λ*

λ and thermal response; non-destructive GPR + water-retention curve methods have quantified water ingress in limestones and underscore why breathable lime layers are preferred (11, 19-21).

In related lime-based composites, PCM-modified mortars have standardized durability protocols (freeze–thaw, salt crystallization) and hotbox thermal testing that we reference for future hygrothermal coupling and durability validation pathways.

3.7 Consistency checks vs. literature

Modeled behavior (amplitude attenuation, phase shift, reduced peaks) is consistent with Mediterranean test-cell measurements on rammed earth walls at Barcelona and Puigverd de Lleida, which documented stable inner-surface temperatures and strong diurnal buffering in massive envelopes(1-3).

4. Results

4.1 Free-float indoor temperature (72 h)

Fig. 5 (summer) and Fig. 6 (winter) compare the free-running indoor surface temperature behind the composite wall and the cement baseline. In both seasons, the composite halves the diurnal indoor amplitude

(≈ ±3 °C at ≈ ±1.5 °C) and increases the phase shift, delaying the indoor peak by several hours relative to outdoors.

The effect is most visible in summer (Fig. 5), where peak temperatures are shaved and troughs are lifted, yielding a narrower, more comfortable band; in winter (Fig. 6), the composite similarly damps swings, improving stability around the mean(1, 2).

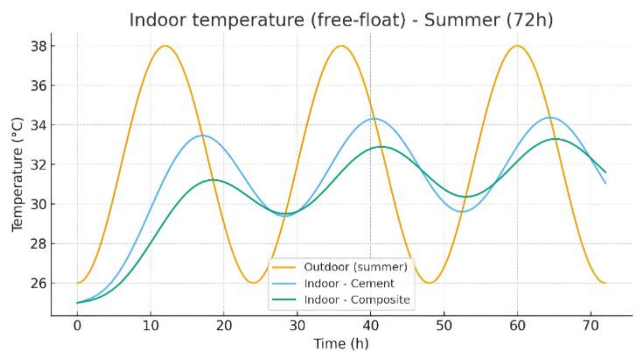

Fig. 5. Summer free-float indoor temperature (72 h): composite vs cement.

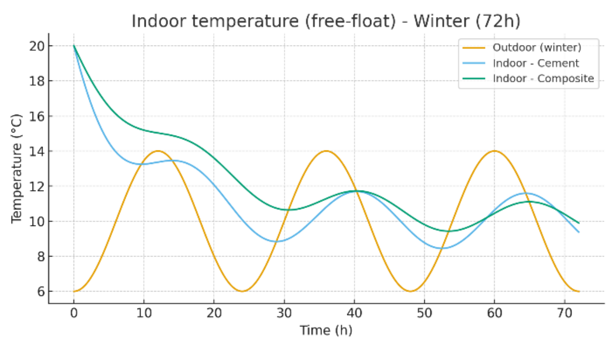

Fig. 6. Winter free-float indoor temperature (72 h): composite vs cement.

4.2 HVAC power and 72-h energy to hold setpoints

Fig. 7 and Fig. 8 show the instantaneous HVAC power needed to clamp the indoor surface to the comfort setpoints (25 °C summer; 20 °C winter). Compared with cement, the composite wall reduces peak power and cuts the 72-h integrated energy. Over the 72-h window used here, the composite achieves substantial savings in summer cooling and meaningful reductions in winter heating, consistent with the free-float improvements above (17, 18).

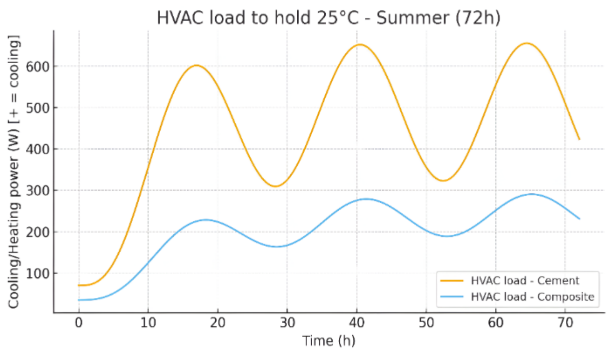

Fig. 7. Summer HVAC power to hold 25 °C (72 h).

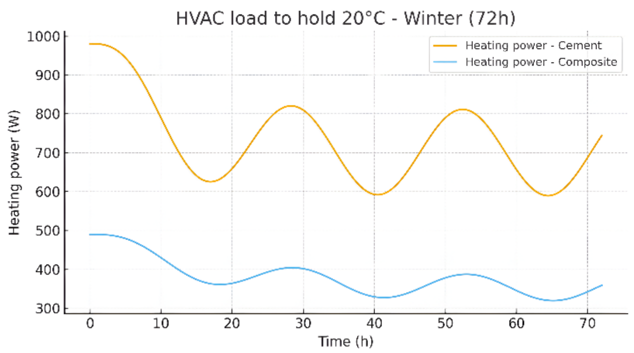

Fig. 8. Winter HVAC power to hold 20 °C (72 h).

4.3 Parametric sweep — core thickness

Fig. 9–10 summarize the thickness sweep Lcore=0.15/0.20/0.30 m at fixed λcore=0.70 W·m⁻¹·K⁻¹) Increasing thickness consistently decreases 72-h energy, with the largest marginal benefit observed from 0.15→0.20 m and further improvement at 0.30 m. The effect is strongest for summer cooling (Fig. 9), where the mass most effectively attenuates the diurnal forcing, and remains significant for winter heating (Fig. 10) through stabilization around the setpoint (22-24).

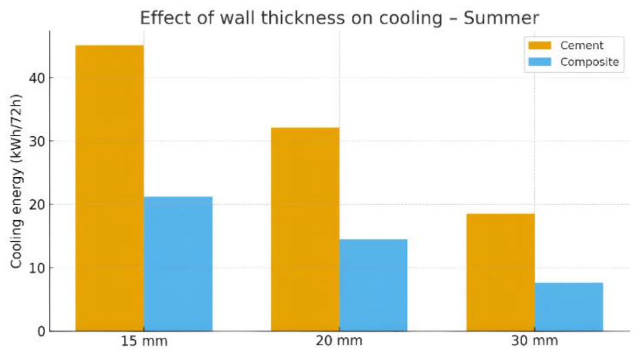

Fig. 9. Cooling energy (72 h) vs. **Lcore** (summer).

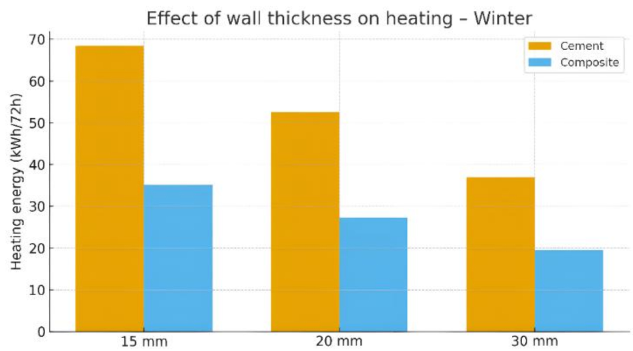

Fig. 10. Heating energy (72 h) vs. **Lcore** (winter)

Key finding. Thickness is the primary lever: sizing the core to 0.20–0.30 m drives most of the energy and comfort gains.

4.4 Parametric sweep — core conductivity

Figures 11–12 show the conductivity sweep (λcore = 0.60, 0.70, 0.80 W·m⁻¹·K⁻¹) at fixed Lcore = 0.20 m.

The 0.60–0.70 band performs best, delivering lower 72-h energy and reduced peaks; at 0.80, benefits erode as the core over-couples to outdoors and peak-shaving weakens (24).

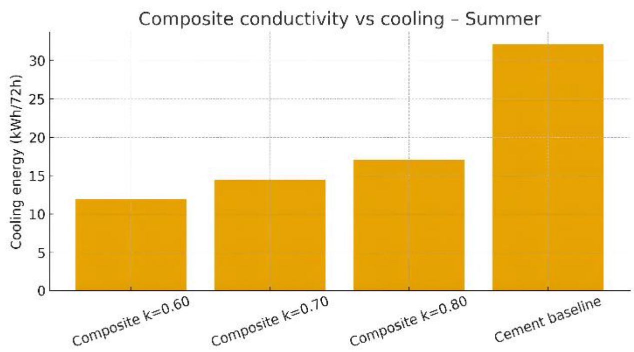

Fig. 11. Cooling energy (72 h) vs. λcore (summer)

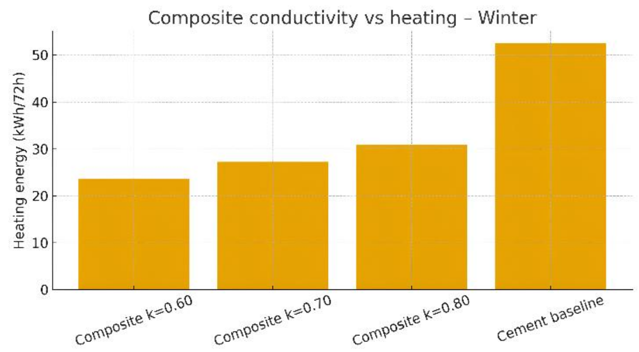

Fig. 12. Heating energy (72 h) vs. λcore (winter)

Design rule. After sizing thickness, tune λ within 0.60–0.70 W m^{-1} K^{-1} to sharpen peak shaving while keeping the mass thermally engaged with the indoor zone.

4.5 Robustness checks and interpretation

- The time-series (Figs. 1 & 3) and the controlled runs (Figs. 2 & 4) tell a consistent story: mass + moderate conductivity = smaller indoor swings, delayed peaks, and less HVAC energy(1-3, 18, 24).
- The parametrics confirm: (i) thickness produces the largest effect size; (ii) conductivity plays a secondary, tuning role; (iii) both seasons benefit, but summer gains are more pronounced due to stronger diurnal forcing.
- These findings align with Mediterranean overheating-risk logic and with experimental evidence that massive, breathable envelopes improve comfort under day–night cycling (17, 25).

5. Discussion

5.1 Implications for Mediterranean overheating risk

Across both free-running and controlled cases, the composite wall reduces indoor temperature amplitude and delays the peak relative to the cement baseline (Figs. 5–8). In dwellings where cooling demand is rising and the dominant forcing is diurnal; this phase shift pushes the indoor maximum into late afternoon/evening precisely when external gains are declining and shading plus night ventilation is most effective. The result is lower cooling needs at the most critical hours (1-3, 17, 25-28).

5.2 Design levers distilled: thickness first, conductivity second

The core thickness Lcore is the primary lever: increasing from 0.15 → 0.20 → 0.30 m lowers 72-h energy, with the largest marginal benefit often from 0.15 to 0.20 m (Figs. 9–10; Tables 2 & 4). Thermal conductivity (λ) then fine-tunes performance: staying within 0.60–0.70 W·m^{-1}·K^{-1} keeps the mass thermally coupled to indoor air while limiting over-coupling to outdoors; moving toward 0.80 gradually erodes peak-shaving (Figs. 11–12; Table 5). Rule of thumb: size Lcore = 0.20–0.30 m, then tune λcore ≈ 0.60–0.70 W·m^{-1}·K^{-1} (13, 14, 17).

5.3 Role of lime-based layers and local sourcing

Lime renders/binders support vapor openness and low-carbon objectives (lower process energy and in-service carbonation), especially when detailing avoids moisture traps. Using local red clay and limestone strengthens NZEB coherence. Thin PCM-modified lime layers could, in future, extend comfort hours, subject to durability validation(4-6).

5.4 Hygrothermal behavior and durability

Moisture state affects the apparent λ and transient response; vapor-open detailing and capillary breaks (at plinths/openings) are essential. In coastal exposure, the surface finish of lime renders governs salt cycling, motivating controlled porosity. A natural next step is to couple heat and moisture in simulation and instrument test walls (T/RH/heat-flux) for seasonal calibration(11, 16, 19-21).

5.5 Sensitivity, limitations, and generalizability

(i) Single-wall modelling: whole-building effects (glazing ratio/orientation, external shading, ventilation control) will modulate gains(18, 22, 27, 29).
(ii) 72-h representative sequences: the next step is multi-site Mediterranean weather files from measurements.
(iii) No PCM in the base case: adding thin PCM layers requires verification of microstructural integrity and cycling stability.
(iv) Execution and interfaces: structural/hygrothermal details do not change the thermal conclusions but determine robustness in practice.

6.Conclusions

The results show that the red clay–limestone–lime composite wall reduces indoor temperature amplitude by nearly half and delays thermal peaks, leading to lower 72 h cooling (summer) and heating (winter) energy demands compared with the cement-based reference wall. The composite also reduces peak HVAC power demand, particularly during summer conditions.

The dominant design lever is core thickness: setting Lcore = 0.20–0.30 m provides robust diurnal buffering, while moderate conductivity (λ ≈ 0.60–0.70 W·m^{-1}·K^{-1}) strengthens peak shaving without decoupling the mass from the indoor zone.

Lime-based, vapor-open finishes further support low-carbon and durability objectives through lower process energy and in-service carbonation potential, and they remain well suited to Mediterranean exposure conditions. Thin PCM-enhanced lime renders may offer additional comfort gains, subject to durability validation.

In practice, combining this composite mass wall with solar shading, night ventilation, and appropriate envelope detailing outlines a pragmatic NZEB pathway for

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Mediterranean multi-storey buildings that leverages local, low-impact resources.

Future work should couple heat and moisture under measured multi-site Mediterranean weather conditions, assess comfort using occupied-zone indicators (e.g., hours of discomfort), and validate performance with instrumented test walls across seasons.

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