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AI-DRIVEN PASSIVE COOLING ASSESSMENT: PREDICTIVE MODELING OF MULTI-LAYERED BUILDING ENVELOPES

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Abstract

Rising energy consumption for building climate control drives the need for alternative cooling approaches that minimize power usage. This investigation examines how wall systems with multiple layers separated by air spaces perform thermally as a strategy for natural temperature regulation. An experimental structure measuring 4 feet by 6 feet was built using locally sourced laterite stone, with an additional outer wall positioned 1.5 feet away from the primary structure on each side. Eight temperature sensors were positioned systematically on interior and exterior wall surfaces to track thermal variations across all orientations. The research sought to measure the insulating capacity of the air space configuration and create forecasting tools for design enhancement. The working assumption suggested that dual-wall construction with intermediate air spacing would substantially limit thermal transfer relative to standard single-layer walls. Advanced computational analysis methods were applied to interpret the intricate thermal dynamics and forecast performance characteristics. Findings revealed considerable temperature differences between external and internal wall surfaces, confirming the air cavity's role as an effective thermal barrier. The application of intelligent data processing facilitated the determination of peak performance scenarios and enabled temperature forecasting based on ambient conditions. This work advances environmentally responsible construction practices by delivering measurable proof of how layered wall assemblies achieve natural cooling, validated through sophisticated analytical methods. The outcomes provide actionable guidance for deploying low-energy building exterior designs, especially applicable to regions experiencing elevated temperatures.

Introduction and Objectives

Global energy consumption continues to escalate, prompting its associated environmental impacts to drive heightened interest in construction methods that prioritize sustainability [1]. Within this context, natural temperature regulation methods have emerged as critical approaches for minimizing power dependence while maintaining comfortable interior conditions [2]. Wall assemblies featuring multiple layers represent an advanced architectural approach that harnesses principles of thermal storage and energy movement to develop high-performance building exteriors [3]. Traditional construction methods typically rely on mechanical climate control systems, accounting for approximately 40% of building energy use in numerous geographical areas [4]. The combination of rapid urban expansion and climbing atmospheric temperatures intensifies the urgency for power-conserving cooling alternatives [5]. Composite wall configurations offer non-mechanical solutions through deliberate placement of construction materials and air spaces to manage thermal flow, substantially decreasing cooling requirements [6]. The present investigation focuses on assessing the thermal effectiveness of composite wall assemblies as a natural cooling methodology [7]. This work analyses how different material selections, structural arrangements, and climatic factors interact to evaluate the temperature-moderating capacity of layered walls and establish ideal design specifications for various climate zones [8]. The outcomes contribute to the growing body of evidence supporting sustainable construction methods and offer practical direction for building professionals seeking to implement power-efficient approaches [9]. The performance of layered

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wall systems stems from their characteristic structural composition [10]. Such assemblies typically incorporate dense heat-storing layers, insulative components, and purposefully positioned air chambers that work in concert to minimize thermal transmission [11]. Heat-absorbing components capture and hold thermal energy during high-temperature periods, while air-filled spaces create insulating barriers that impede heat movement [12]. Thoughtful arrangement of these layers can create time delays in thermal transfer, relocating maximum interior temperatures to periods when they cause less discomfort [13].The study hypothesizes that multi-layered walls with an air gap of 1.5 feet will reduce significantly the heat transfer to the interior spaces compared to conventional single-wall construction with the laterite stone's thermal mass properties further enhancing this effect across different times of day and cardinal orientations. The primary objective of this research are to evaluate the effectiveness of multi-layered wall system with air gap as a passive cooling strategy by: analysing temperature variations between inner and outer walls across all four cardinal directions; quantifying the thermal performance of the 1.5 foot air gap between laterite stone walls in reducing heat transfer; determining the system's effectiveness during different times of day and identifying peak performance periods; establishing corrections between external environmental conditions and the temperature differential achieved; and assessing laterite stone's potential as a thermal mass material in a multi-layered wall construction. The scope of this study encompasses the construction and monitoring of a scale model house (4feet x 6 feet) built with locally available laterite stone, featuring a secondary external wall surrounding all four sides with 1.5-foot air gap between primary and secondary walls, with walls aligned to cardinal directions for comprehensive performance evaluation.

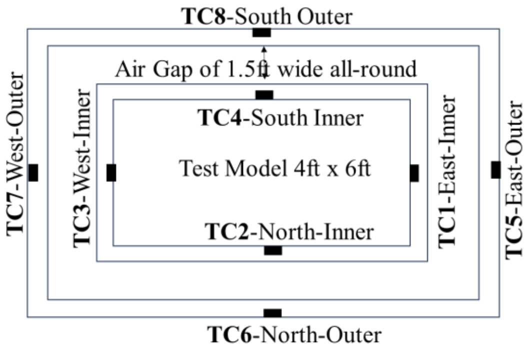

Figure-1: Schematic Diagram of the Test Model

Temperature data collection utilized a digital logging device equipped with thermocouple-type sensors [14]. Sensor positioning consisted of one unit on each directional face (north, south, east, west) of the internal wall's interior surface, plus one unit on each corresponding directional face of the external wall's outer surface, enabling thermal data capture from all eight measurement points. This monitoring configuration establishes a thorough methodology for quantifying temperature variations throughout the layered wall assembly and assessing its performance as a natural cooling mechanism. The experimental design specifically addresses the problem of unwanted thermal gain penetrating building enclosures, which presents a significant challenge in hot and humid climate zones [15]. Through the combination of laterite stone construction with an intermediate air space, the system effectively manages thermal energy movement through structural components. The four-directional monitoring arrangement was developed to examine how thermal loads differ based on directional exposure [16]. This consideration proves particularly critical given that solar radiation impacts and resulting heat accumulation show marked differences when comparing east-west versus north-south building faces [17]. The strategic distribution of eight temperature sensors throughout both inner and outer wall surfaces guarantees accurate tracking of temperature variations and time-delayed heat transmission within the composite wall structure. The selected 4ft × 6ft footprint offers an appropriate scale that harmonizes practical considerations with authentic thermal performance

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characteristics. This size proves adequate for demonstrating real thermal behavior patterns while keeping experimental variables manageable, and remains compact enough to control construction expenditures and procedural complications without compromising research integrity. Laterite stone, being regionally accessible and widely utilized in building applications, exhibits favorable heat storage characteristics, exemplifies environmentally responsible material selection, and facilitates practical application of research findings to full-scale construction projects.

Figure 2: Experimental Setup

The 1.5ft spacing between wall layers was selected to permit adequate air movement, establish a substantial thermal insulation zone, and reflect a feasible dimension for implementation in actual building projects. The balanced arrangement of temperature sensors supports refined comparative evaluation across different directional exposures, concurrent tracking of internal and external thermal states, and thorough documentation of temperature distribution patterns [18].

Material Properties and Characterization:

The thermal performance of the multi-layered wall system depends fundamentally on the physical and thermal properties of the constituent materials. Laterite stone, the primary construction material, exhibits characteristic properties that make it suitable for passive cooling applications. The material properties of laterite stone and comparative materials used in the analysis are presented below.

Thermal Properties:

Laterite stone demonstrates a thermal conductivity of approximately 0.92 W/m·K, which is moderately lower than concrete but slightly higher than conventional brick masonry [19]. The specific heat capacity of laterite stone ranges around 900 J/kg·K, indicating reasonable heat storage capability [20]. This thermal mass property allows the material to absorb heat during peak temperature periods and release it gradually during cooler hours [21]. The density of laterite stone typically falls within the range of 1800-1900 kg/m³, with the test specimens exhibiting values around 1850 kg/m³ [22]. The thermal diffusivity, calculated from thermal conductivity, specific heat, and density, was determined to be approximately 5.5×10^{-7} m²/s [23].

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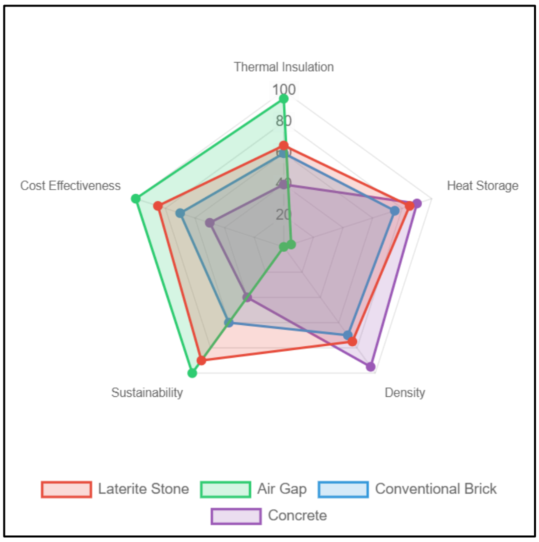
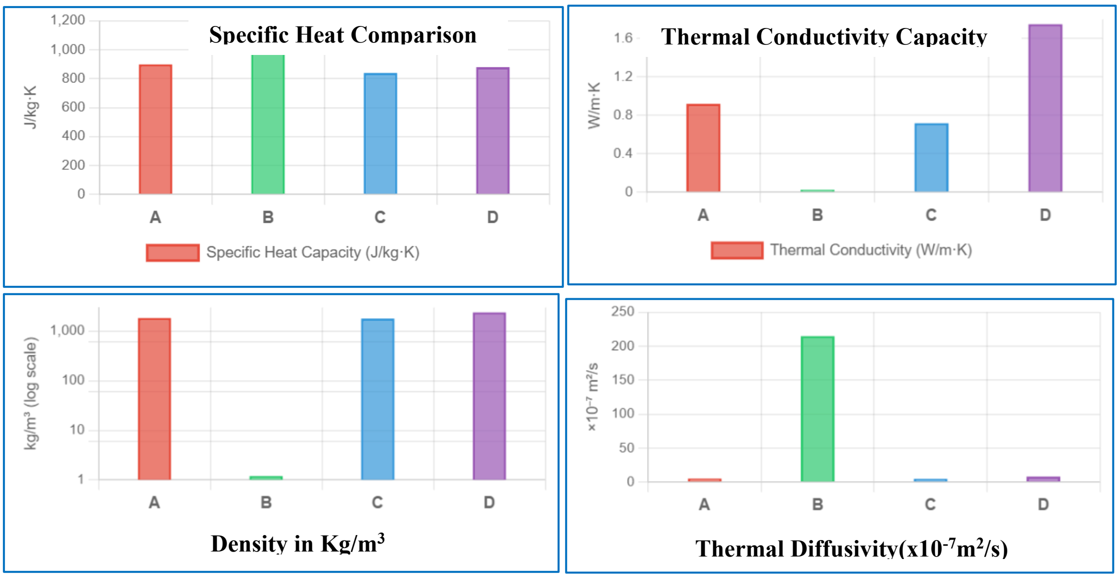


Figure 3: Comprehensive Material Properties Comparison



The air gap, serving as the intermediate layer between the primary and secondary walls, possesses significantly different thermal characteristics. Air at atmospheric conditions exhibits extremely low thermal conductivity of approximately 0.026 W/m·K, making it an excellent thermal insulator [24]. The specific heat capacity of air is 1005 J/kg·K, while its density at standard conditions is approximately 1.2 kg/m³ [25]. The thermal diffusivity of air is considerably higher at 215 × 10^{-7} m²/s due to its low density [26].

For comparative analysis, conventional brick masonry shows thermal conductivity values around 0.72 W/m·K with specific heat capacity of 840 J/kg·K and density of approximately 1800 kg/m³ [27]. Concrete, another common building material, exhibits higher thermal conductivity of 1.75 W/m·K, specific heat of 880 J/kg·K, and density of 2400 kg/m³ [28].

Table 1: Comparative Material Properties

Property	Laterite Stone	Air Gap (1.5ft)	Conventional Brick	Concrete
Thermal Conductivity (W/m·K)	0.92 [19]	0.026 [24]	0.72 [27]	1.75 [28]
Specific Heat (J/kg·K)	900 [20]	1005 [25]	840 [27]	880 [28]
Density (kg/m³)	1850 [22]	1.2 [25]	1800 [27]	2400 [28]

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Thermal Diffusivity (×10⁻⁷ m²/s)	5.5 [23]	215.0 [26]	4.8 [27]	8.3 [28]

Material Properties and Performance Indicators:

The thermal performance of multi-layered wall systems is fundamentally determined by the physical and thermal properties of constituent materials. **Figure 3** presents a comprehensive comparison of key material properties including thermal conductivity, specific heat capacity, density, and thermal diffusivity for laterite stone, air gap, conventional brick, and concrete.

The graphical analysis reveals the complementary nature of laterite stone and air gap in the multi-layered system. The air gap demonstrates exceptional thermal insulation (thermal conductivity of 0.026 W/m·K), while laterite stone provides adequate thermal mass (specific heat of 900 J/kg·K and density of 1850 kg/m³) for heat storage and gradual release [19, 20, 22, 24]. The radar chart illustrates the multi-dimensional performance characteristics, showing how the combination of these materials achieves balanced performance across thermal insulation, heat storage, sustainability, and cost-effectiveness parameters. These property relationships validate the observed >5°C temperature reduction and thermal stability achieved in the experimental setup.

Results and Discussions:

The thermal performance analysis of the multi-layered wall system yielded two significant findings. First, the introduction of a 1.5ft air gap between the primary laterite stone wall and the secondary external wall demonstrated a marked cooling effect, achieving more than 5 degrees reduction in core wall temperatures.

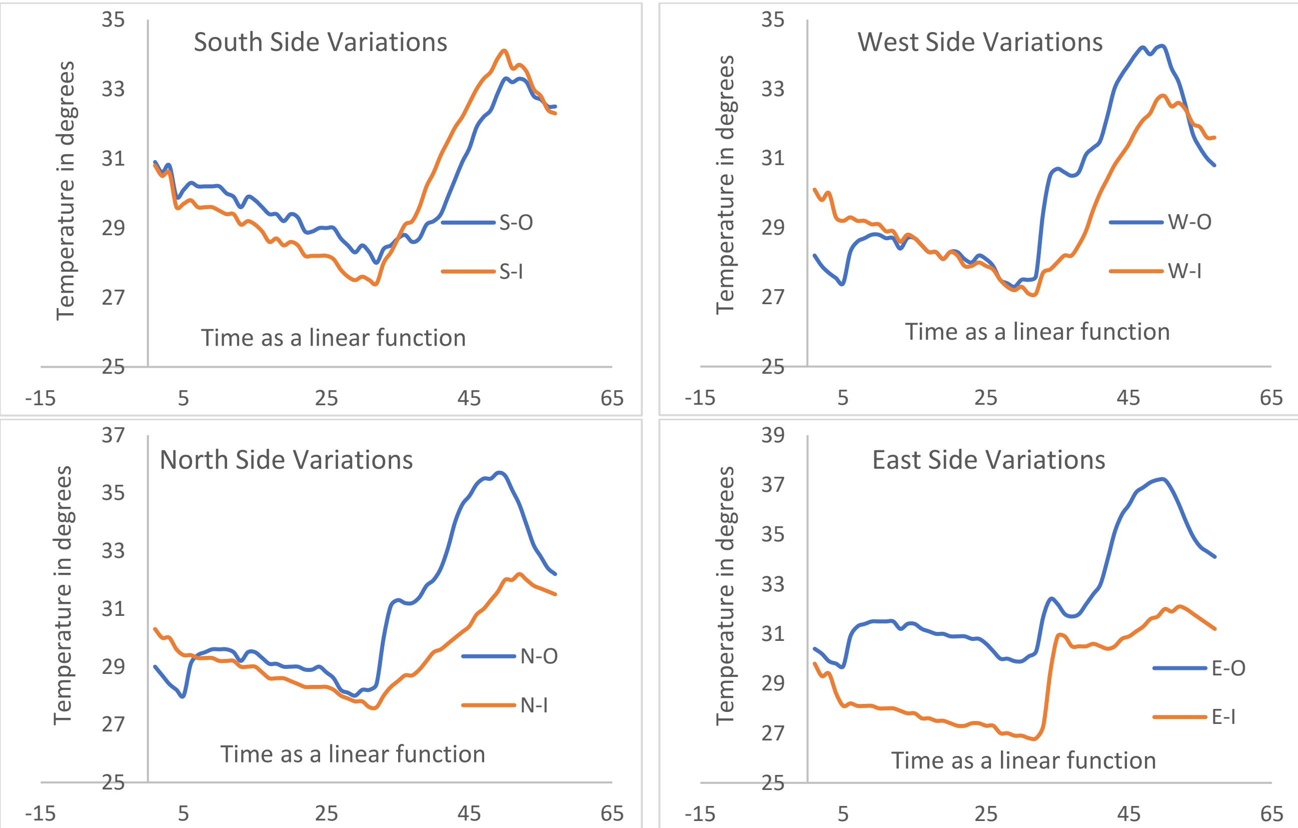

Figure-4:Temperature variations across walls in 4 directions *before* introduction of Air Gap

Second, and notably, the system effectively nullified the decrement factor across all four cardinal directions, indicating superior thermal regulation. This dual impact - both the absolute temperature

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reduction and the elimination of the decrement factor - suggests that the air gap serves as a highly effective thermal buffer zone.

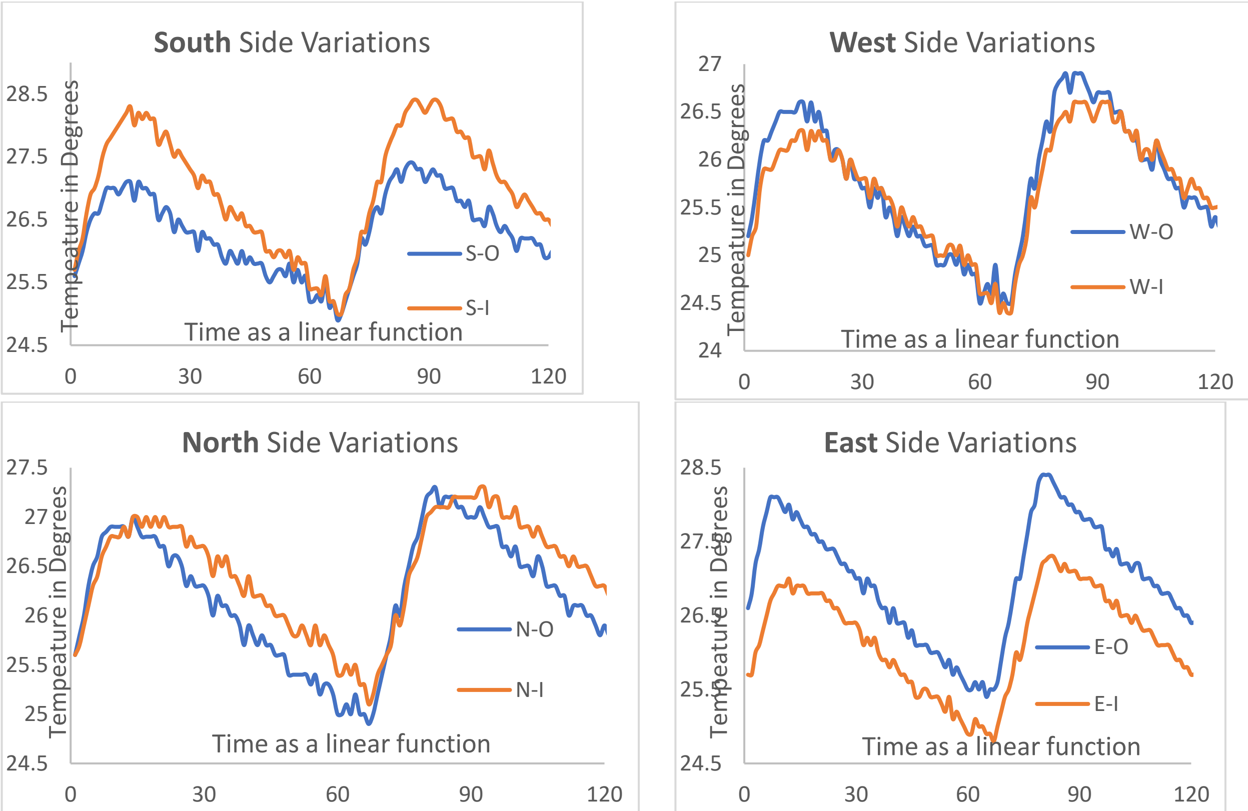

Figure 5: Temperature Readings on 4 Sides *after* introduction of Air Gap

The neutralization of the decrement factor is particularly significant as it indicates more stable and comfortable indoor conditions, minimizing temperature fluctuations in the core rooms. These findings collectively demonstrate that the multi-layered wall system not only reduces absolute temperatures but also maintains more consistent thermal conditions, thereby enhancing occupant comfort through purely passive means.

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