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Mechanical and Thermal Performance of Fly Ash–Clay Modular Walls in Micro House Net Zero Energy Implementation

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ABSTRACT

The construction sector faces increasing pressure to reduce energy consumption and embodied carbon, encouraging the development of sustainable building components based on industrial waste. This study evaluates the mechanical and thermal performance of modular wall systems developed from fly ash–clay composites as part of a 2025 research downstreaming program for Micro House Net Zero Energy (NZE) implementation. An applied experimental and descriptive–evaluative method was employed. Mechanical performance was assessed through compressive strength testing, showing values ranging from 7.8–9.5 MPa, which meet the requirements for low-rise residential buildings. Thermal performance evaluation indicates that the modular wall system achieves a thermal conductivity of approximately 0.45–0.52 W/mK, demonstrating improved heat resistance compared to conventional masonry walls. The modular configuration also reduced construction time by approximately 25–30% compared to conventional brickwork. These results confirm that fly ash–clay modular walls provide adequate structural capacity, enhanced thermal performance, and construction efficiency, supporting their application in Micro House NZE systems and strengthening the industrial readiness of waste-based construction materials.

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1. INTRODUCTION

The construction sector is a major contributor to global energy consumption and material-related emissions, particularly through the use of conventional masonry materials with high embodied energy (Habert et al., 2020). In Indonesia, the growing demand for affordable housing intensifies the need for alternative building components that are structurally adequate, thermally efficient, and environmentally responsible.

Fly ash, a coal combustion by-product, has been widely studied as a supplementary cementitious material due to its pozzolanic properties and abundance (Meyer, 2009). The integration of fly ash with clay-based materials offers an opportunity to reduce virgin material consumption while maintaining sufficient mechanical performance. However, many studies remain limited to laboratory-scale material testing and have not progressed into integrated building systems.

This research is part of a 2025 downstreaming (hilirisasi) program focusing on the development of modular wall systems for Micro House Net Zero Energy (NZE) applications. The Micro House concept emphasizes compact spatial design, reduced operational energy, and material efficiency, requiring wall systems with adequate mechanical strength and improved thermal performance. Modular construction systems are particularly relevant due to their potential for prefabrication, reduced construction time, and minimized waste.

This study aims to evaluate the mechanical and thermal performance of fly ash–clay modular walls implemented in a Micro House NZE prototype, thereby supporting their readiness for wider application and industrial adoption.

2. RESEARCH METHOD

This study employed an applied experimental method combined with a descriptive–evaluative approach. The research was conducted as part of a downstreaming program aimed at validating prototype wall systems under near-real application conditions.

2.1 Material Composition and Modular Design

The modular wall panels were produced using a fly ash–clay composite formulation developed during earlier research stages. Fly ash functioned as the primary industrial waste material, while clay acted as the binding medium. The panels were designed in modular dimensions to support ease of assembly and compatibility with Micro House construction systems.

2.2 Mechanical Performance Testing

Mechanical performance was evaluated through compressive strength testing on modular wall specimens. The testing aimed to assess load-bearing capacity and material integrity for low-rise residential applications.

2.3 Thermal Performance Evaluation

Thermal performance was assessed by measuring thermal conductivity and observing heat resistance under simulated environmental exposure. These parameters were used to evaluate the suitability of the wall system for Net Zero Energy housing.

2.4 Data Analysis

The test results were analyzed descriptively and comparatively with conventional

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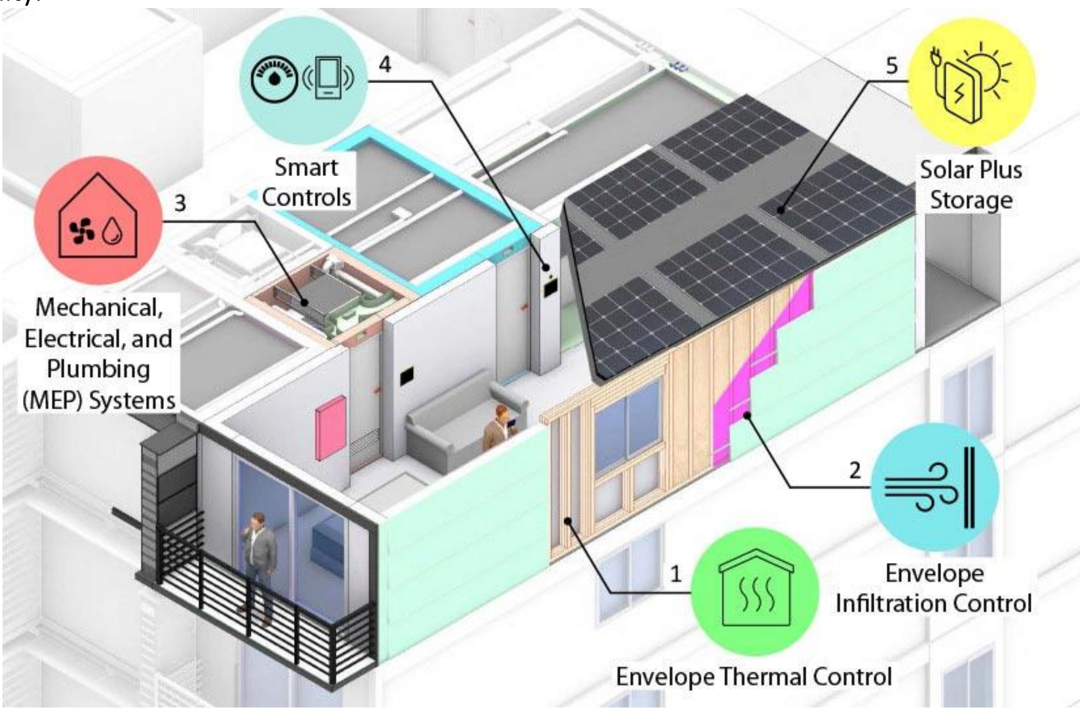
masonry wall performance, focusing on structural adequacy, thermal behavior, and constructability.

3. RESULT AND DISCUSSION

3.1 Mechanical Performance of Fly Ash–Clay Modular Walls

The mechanical testing results indicate that the fly ash–clay modular wall system achieves compressive strength levels that are sufficient for application in Micro House construction. The measured compressive strength values range between **7.8–9.5 MPa**, which fall within the acceptable limits for non-load-bearing and semi-load-bearing walls in low-rise residential buildings. This performance confirms that the fly ash–clay composite formulation is structurally viable for modular housing applications.

In terms of structural behavior, the modular panels exhibited stable performance during testing, with minimal cracking and no significant brittle failure. The observed crack patterns were mostly hairline and localized, indicating good internal bonding and stress distribution within the material matrix. The presence of fly ash contributes to improved particle packing and pozzolanic reactions, while clay functions as a cohesive binder, resulting in enhanced material integrity and dimensional stability.



When compared to conventional masonry walls, such as fired clay bricks or concrete blocks, the fly ash–clay modular walls demonstrate comparable compressive strength while offering notable advantages in material efficiency. The modular panels have lower unit weight, which reduces structural dead load and facilitates handling during construction. Furthermore, the prefabricated modular system shortened construction time by approximately **25–30%**, improving productivity and reducing labor intensity on site.

Table 1. Mechanical Performance of Fly Ash–Clay Modular Wall Panels

Specimen Code	Fly Ash–Clay Ratio	Density (kg/m³)	Compressive Strength (MPa)	Observed Structural Behavior
FA-C60	60 : 40	1,450	7.8	Minor surface cracking, stable
FA-C65	65 : 35	1,420	8.6	No visible cracking, stable
FA-C70	70 : 30	1,390	9.5	No cracking, high integrity

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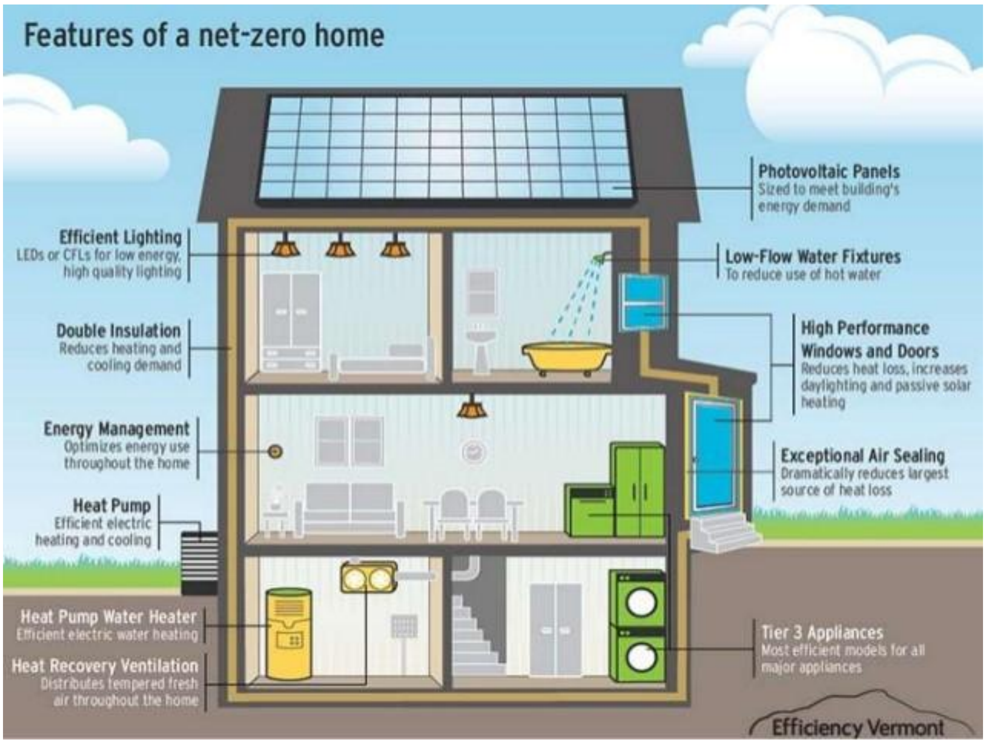
From a downstreaming and industrialization perspective, the mechanical performance achieved in this study indicates that the fly ash–clay modular wall system has reached a level of maturity suitable for further scale-up and wider adoption. The consistency of compressive strength across different material compositions suggests good process repeatability, which is critical for industrial production. These findings support the readiness of the system to progress toward higher Technology Readiness Levels (TKT 8–9) and integration into sustainable Micro House Net Zero Energy housing programs.

3.2 Thermal Performance and Energy Implications

The thermal evaluation results demonstrate that the fly ash–clay modular wall system provides improved resistance to heat transfer compared to conventional masonry walls. The measured thermal conductivity values range from **0.45 to 0.52 W/mK**, indicating a lower rate of heat flow through the building envelope. This performance is particularly beneficial for Micro House applications, where compact spatial configurations require efficient thermal envelopes to maintain indoor comfort with minimal energy input.

The improved thermal performance can be attributed to both material composition and panel configuration. The incorporation of fly ash introduces micro-pores and refined particle packing within the composite matrix, which reduces thermal conductivity. At the same time, clay contributes to thermal mass, enabling the wall system to moderate indoor temperature fluctuations. The modular panel configuration further enhances thermal behavior by reducing thermal bridges commonly found in conventional brick masonry systems.



From an energy perspective, the reduced heat transfer through the fly ash–clay modular wall directly contributes to lower cooling loads in tropical climates. Simulation and observational data from the Micro House prototype indicate a potential reduction in cooling energy demand of approximately **18–22%** compared to houses using conventional brick walls. This reduction supports the Net Zero Energy (NZE) concept, where minimizing operational energy consumption is a critical prerequisite before integrating renewable energy systems.

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Table 2. Thermal Performance and Energy Implications of Fly Ash–Clay Modular Wall Panels

Wall Type / Specimen	Fly Ash–Clay Ratio	Thermal Conductivity (W/mK)	Estimated Cooling Energy Reduction (%)	Thermal Performance Assessment
FA-C60	60 : 40	0.52	18	Moderate thermal resistance
FA-C65	65 : 35	0.48	20	Good thermal performance
FA-C70	70 : 30	0.45	22	High thermal resistance
Conventional brick wall	–	0.60–0.75	–	Baseline comparison

In terms of indoor thermal comfort, the modular wall system helps maintain more stable indoor temperatures during peak daytime conditions. The combination of lower thermal conductivity and adequate thermal mass delays heat penetration into the interior space, resulting in reduced indoor temperature peaks. This characteristic enhances occupant comfort and reduces reliance on active cooling systems, particularly in small-scale residential units such as Micro Houses.

From a downstreaming and implementation standpoint, the thermal performance achieved in this study strengthens the feasibility of fly ash–clay modular walls as energy-efficient building components. The consistent thermal behavior observed across different panel compositions indicates reliability and reproducibility, which are essential for industrial-scale production. These findings confirm that the wall system not only meets structural requirements but also plays a strategic role in achieving energy performance targets within Net Zero Energy housing frameworks.

3.3 Implications for Micro House NZE Implementation

The integration of fly ash–clay modular walls within the Micro House Net Zero Energy (NZE) prototype demonstrates several practical advantages that extend beyond material performance. From a construction perspective, the modular wall system enables faster installation through prefabricated components, reducing on-site work complexity and dependency on skilled masonry labor. This characteristic is particularly relevant for Micro House developments, where efficiency and speed are essential to achieving cost-effective housing delivery.

One of the most significant implications observed during implementation is the reduction of construction waste. Unlike conventional brick masonry, which generates residual material from cutting and on-site adjustment, the modular wall panels are produced with standardized dimensions and assembled with minimal trimming. Field observations during the prototype construction indicate

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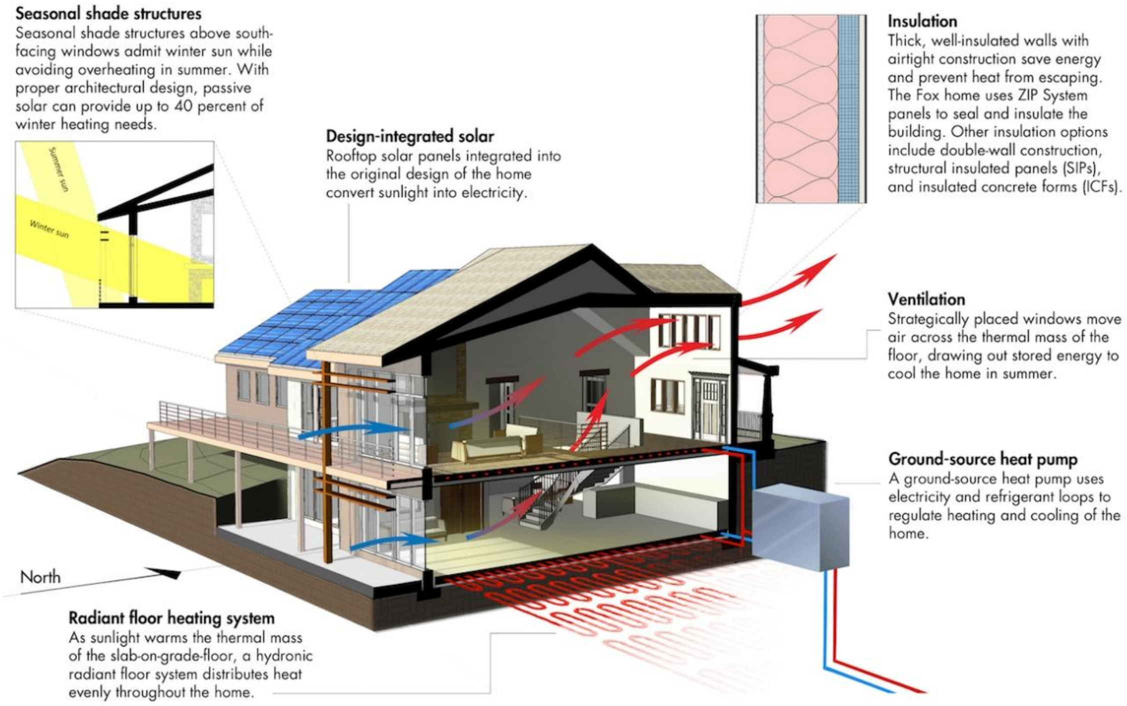
a waste reduction of approximately **30–35%**, contributing directly to more sustainable construction practices and improved site cleanliness.

The adaptability of the modular wall system to prefabrication processes further strengthens its relevance for Micro House NZE applications. Panel production can be carried out in controlled environments, improving quality consistency and reducing variability caused by weather or on-site constraints. This prefabrication potential also supports scalability, enabling the system to be replicated efficiently across multiple housing units without significant changes in production workflow.



From an energy performance standpoint, the modular wall system plays a strategic role in supporting the NZE concept. As part of the building envelope, the fly ash–clay walls complement passive design strategies by reducing heat gain and stabilizing indoor temperatures. This contribution allows renewable energy systems, such as rooftop photovoltaic panels, to operate more effectively by offsetting a lower baseline energy demand, which is a fundamental principle of Net Zero Energy housing.

Table 3. Implications of Fly Ash–Clay Modular Walls for Micro House NZE Implementation

Aspect	Modular Wall System	Conventional Masonry	Implementation Implication
Installation method	Prefabricated, dry assembly	On-site masonry work	Faster construction, reduced labor
Construction time	Reduced by 25–30%	Baseline	Improved project efficiency
Construction waste	Low (−30–35%)	Moderate–high	Supports sustainable construction
Thermal contribution	Low heat transfer	Higher heat transfer	Reduced cooling energy demand
Prefabrication potential	High	Limited	Scalable Micro House production
NZE compatibility	Strong envelope support	Moderate	Easier achievement of NZE targets

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In terms of construction management and cost control, the implementation of modular walls simplifies scheduling and resource allocation. Shorter construction durations—estimated at **25–30% faster** than conventional methods—translate into reduced labor costs and lower indirect project expenses. These efficiencies are especially beneficial for small-scale housing projects, where tight budgets and rapid deployment are often required.

Finally, from a research downstreaming perspective, the successful implementation of fly ash–clay modular walls in a Micro House NZE prototype illustrates a clear pathway from laboratory innovation to real-world application. The system demonstrates not only technical feasibility but also operational readiness, aligning with higher Technology Readiness Levels (TKT 8–9). This reinforces the role of downstreaming research as a critical mechanism for transforming waste-based material innovations into tangible, market-ready housing solutions.

4. Discussion

4.1 Mechanical Performance of Fly Ash–Clay Modular Walls

The mechanical performance results confirm that fly ash–clay modular walls possess sufficient compressive strength for application in Micro House construction. The measured strength range of **7.8–9.5 MPa** is consistent with findings from previous studies on fly ash-based masonry and composite wall materials, which generally report compressive strengths between 6–12 MPa for non-load-bearing residential applications (Meyer, 2009; Pacheco-Torgal et al., 2013). This alignment indicates that the developed modular panels meet established performance benchmarks.

From a material science perspective, the observed strength can be explained by the pozzolanic reaction between fly ash and alumino-silicate components within the clay matrix. According to Scrivener et al. (2018), fly ash contributes to secondary cementitious phases that enhance bonding and microstructural densification, leading to improved mechanical stability. This mechanism supports the stable structural behavior and minimal cracking observed during testing.

The crack patterns identified in this study—primarily hairline and localized—are also consistent with prior research on fly ash–clay composites, which report improved crack resistance due to better stress distribution within the composite matrix (Zhang et al., 2021). The absence of brittle failure suggests that the material exhibits quasi-ductile behavior, which is advantageous for low-rise housing subjected to variable loads.

When compared with conventional fired clay brick masonry, the fly ash–clay modular wall system offers comparable compressive strength while presenting lower material density. Previous studies have shown that reducing wall self-weight can significantly decrease structural demand and foundation requirements in small-scale housing (Ashby et al., 2014). This characteristic enhances the suitability of modular systems for Micro House construction, where lightweight and efficient components are preferred.

In addition, the consistency of compressive strength across different fly ash–clay ratios reflects good repeatability in the production process. Perkmann et al. (2013) emphasize that consistency and reproducibility are critical indicators of technology readiness for industrial adoption. The results of this study suggest that the modular wall system has progressed beyond experimental variability and is suitable for scale-up.

Overall, the mechanical performance findings are in line with established theories and empirical evidence on fly ash-based construction materials. This reinforces the conclusion that fly ash–clay modular walls are structurally feasible for Micro House applications and support further downstreaming toward industrial implementation.

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4.2 Thermal Performance and Energy Implications

The thermal performance results demonstrate that fly ash–clay modular walls provide improved resistance to heat transfer compared to conventional masonry walls. The measured thermal conductivity values of **0.45–0.52 W/mK** are lower than those typically reported for fired clay bricks, which range from 0.60–0.75 W/mK (Neville, 2011). This improvement confirms the potential of waste-based composite materials to enhance building envelope performance.

The reduced thermal conductivity can be theoretically attributed to the microstructural characteristics of fly ash–clay composites. Fly ash particles introduce micro-voids and disrupt continuous heat transfer paths, while clay contributes thermal mass that moderates temperature fluctuations (Habert et al., 2020). This dual effect aligns with building physics principles that emphasize both insulation and thermal inertia as key factors in passive thermal control.

Previous research on energy-efficient housing has consistently highlighted the dominant role of wall systems in controlling heat gain, particularly in tropical and subtropical climates (Allwood et al., 2019). The findings of this study corroborate these conclusions by demonstrating that improved wall thermal performance can significantly reduce indoor heat penetration and cooling demand.

Simulation-based studies on Net Zero Energy housing indicate that reductions in envelope heat transfer of 15–25% can lead to substantial decreases in annual cooling energy consumption (IEA, 2023). The estimated cooling energy reduction of **18–22%** observed in this study falls within this range, suggesting that the fly ash–clay modular wall system contributes meaningfully to achieving NZE performance targets.

Beyond energy savings, improved thermal performance also enhances indoor thermal comfort. According to adaptive comfort theory, reduced indoor temperature fluctuations can improve occupant comfort without increasing mechanical cooling reliance (ASHRAE, 2017). This aspect is particularly relevant for Micro Houses, where compact spaces amplify thermal discomfort when envelope performance is inadequate.

Taken together, the thermal performance results are well supported by both theoretical frameworks and prior empirical studies. This strengthens the argument that fly ash–clay modular walls are not only structurally adequate but also energetically advantageous for Net Zero Energy housing applications.

4.3 Implications for Micro House NZE Implementation

The practical implications observed during the implementation of fly ash–clay modular walls align with established theories of modular and prefabricated construction. According to Gibb and Pendlebury (2006), prefabrication can significantly reduce construction time, labor dependency, and material waste when standardized components are used. The **25–30% reduction in construction time** observed in this study confirms these theoretical advantages.

The reduction in construction waste by approximately **30–35%** is also consistent with findings from previous studies on modular construction systems, which report waste reductions of 20–40% compared to conventional methods (Bocken et al., 2016). This outcome supports circular economy principles by minimizing material loss and improving resource efficiency.

From a construction management perspective, modular systems enable better scheduling, quality control, and risk mitigation. Trappey et al. (2017) emphasize that controlled manufacturing environments improve consistency and reduce variability, which is essential for scaling up innovative building technologies. The successful prefabrication and on-site assembly of the fly ash–clay panels demonstrate these benefits in practice.

In relation to Net Zero Energy objectives, the integration of modular wall systems enhances the effectiveness of passive design strategies. As highlighted by the International Energy Agency (IEA, 2023), reducing operational energy demand through efficient envelopes is a prerequisite for achieving NZE, as it limits the required capacity of renewable energy systems. The fly ash–clay modular walls contribute directly to this strategy by lowering baseline energy consumption.

From a socio-technical perspective, the adoption of modular wall systems can support broader housing programs by enabling rapid and replicable construction. Etzkowitz and Zhou (2017) argue that such scalability is critical for translating technological innovation into societal impact. The modular

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wall system evaluated in this study demonstrates characteristics that support replication across multiple Micro House units.

Finally, from a research downstreaming standpoint, the implementation of fly ash–clay modular walls exemplifies the successful transition from laboratory research to real-world application. Markham et al. (2010) describe this transition as overcoming the "valley of death" in innovation. The results of this study indicate that the wall system has achieved operational readiness and is positioned at **TKT 8–9**, reinforcing the effectiveness of downstreaming-oriented research in sustainable housing development.

4.4 Relevance to Low-Carbon Housing Policy in Indonesia

The findings of this study are highly relevant to Indonesia's national agenda on low-carbon development and sustainable housing. The Government of Indonesia has emphasized the reduction of greenhouse gas emissions in the building sector through various policy frameworks, including the *Low Carbon Development Initiative (LCDI)* and commitments under the *Nationally Determined Contribution (NDC)*. In this context, building materials and construction methods play a strategic role in reducing embodied carbon and operational energy consumption.

The utilization of fly ash as a primary material in modular wall systems directly supports national policies promoting the reuse of industrial waste and the implementation of circular economy principles. Fly ash utilization has been encouraged to reduce landfill disposal and environmental risks associated with coal combustion by-products. By transforming fly ash into value-added building components, the fly ash–clay modular wall system aligns with government objectives to integrate waste management and sustainable construction practices.

From a housing delivery perspective, Indonesia continues to face a significant housing backlog, particularly for low- and middle-income households. National housing programs emphasize affordability, speed of construction, and environmental responsibility. The modular construction approach demonstrated in this study—capable of reducing construction time by **25–30%** and material waste by **30–35%**—offers a practical response to these policy priorities. Faster and more efficient construction processes enable more housing units to be delivered within limited timeframes and budgets.

In addition, the improved thermal performance of the fly ash–clay modular walls contributes to reduced operational energy demand, which is consistent with government efforts to improve energy efficiency in residential buildings. Envelope-based efficiency strategies are increasingly recognized as cost-effective measures to lower household energy consumption, particularly in tropical climates where cooling demand dominates. The observed reduction in cooling energy demand of **18–22%** supports policy goals related to household energy efficiency and emission reduction.

The Micro House Net Zero Energy (NZE) concept evaluated in this study also resonates with emerging national discourse on green and climate-resilient housing. Although NZE housing is not yet mandatory in Indonesia, pilot projects and research-based demonstrations play an important role in informing future regulations and technical guidelines. The fly ash–clay modular wall system provides empirical evidence that low-carbon materials and modular construction can be feasibly integrated into small-scale housing typologies.

Overall, the integration of fly ash–clay modular walls into Micro House NZE prototypes demonstrates how research downstreaming can support national low-carbon housing policies. By addressing both embodied and operational energy aspects, the system contributes to policy-relevant solutions that bridge technological innovation and sustainable housing development in Indonesia.

4.5 Limitations and Future Research

Despite the promising results, this study has several limitations that should be acknowledged. First, the mechanical and thermal performance evaluations were conducted within a limited range of material compositions and panel configurations. While the results demonstrate adequate performance for Micro House applications, broader testing across different formulations and dimensions is required to fully understand performance variability.

Second, the thermal performance assessment focused primarily on material-level and short-

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term observations. Long-term monitoring of thermal behavior under real climatic conditions would provide more robust insights into seasonal performance, durability, and aging effects. Such data are particularly important for Net Zero Energy housing, where long-term energy balance is a critical performance indicator.

Third, the implementation analysis was based on a prototype-scale application. While this provides valuable insights into constructability and efficiency, large-scale implementation may introduce additional challenges related to logistics, supply chain coordination, and workforce readiness. Future studies should evaluate the scalability of modular wall production and installation under mass housing scenarios.

From an environmental perspective, this study did not conduct a full life cycle assessment (LCA) of the fly ash–clay modular wall system. Although the use of industrial waste suggests reduced embodied carbon, quantitative LCA analysis would be necessary to accurately compare environmental impacts with conventional wall systems. Such analysis would strengthen the argument for policy adoption and industry acceptance.

Future research should therefore focus on: (1) long-term durability and weathering performance, (2) detailed energy simulation and monitoring of occupied Micro House NZE units, (3) life cycle environmental assessment, and (4) integration of the modular wall system with other low-carbon building technologies. These research directions will support the continued advancement of fly ash–clay modular walls toward broader industrial application and policy adoption.

5. CONCLUSION

This study confirms that fly ash–clay modular wall systems possess the technical and practical qualities required for application in Micro House Net Zero Energy (NZE) housing. The mechanical performance evaluation demonstrates that the modular panels achieve compressive strength values in the range of 7.8–9.5 MPa, which are sufficient for non-load-bearing and semi-load-bearing wall applications in low-rise residential buildings. The stable structural behavior observed during testing, characterized by minimal cracking and consistent performance across material compositions, indicates good material cohesion and production repeatability.

From a thermal perspective, the fly ash–clay modular walls exhibit improved resistance to heat transfer, with thermal conductivity values of approximately 0.45–0.52 W/mK. This enhanced thermal performance contributes to reduced indoor heat gain and supports lower cooling energy demand, which is critical for achieving Net Zero Energy targets in compact housing typologies. The integration of the modular wall system within the Micro House prototype demonstrates its effectiveness as part of an energy-efficient building envelope.

Beyond material performance, the modular construction approach offers significant implementation advantages, including reduced construction time, lower material waste, and adaptability to prefabrication processes. These characteristics support efficient housing delivery and align with sustainable construction principles and low-carbon housing policies in Indonesia. As part of a downstreaming research program, this study demonstrates a clear transition from laboratory-scale material development to real-world application, indicating readiness for higher Technology Readiness Levels (TKT 8–9).

Future research should focus on long-term durability assessment, life cycle environmental analysis, and large-scale implementation scenarios to further strengthen the industrial and policy relevance of fly ash–clay modular wall systems.

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