Mechanical Characterization and Thermal Insulation Potential of Hybrid Composites for Energy-Efficient Roofing Applications

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ABSTRACT

This study aims to investigate the mechanical properties and thermal insulation potential of hybrid composites reinforced with palm fiber (ijuk) and durian peel fiber for energy-efficient roofing applications. From an electrical engineering perspective, roofing materials play a crucial role in building energy systems, as they influence heat transfer and the operational load of Heating, Ventilation, and Air Conditioning (HVAC) systems.The composites were fabricated using polyester resin with composition variations of 60/20/20, 70/15/15, 80/10/10, and 90/5/5 through the hand lay-up method. An alkali treatment using 1% NaOH was applied to enhance interfacial bonding between the fibers and the matrix. Mechanical testing was conducted using a Universal Testing Machine (UTM) in accordance with ASTM D695 standards. The results indicate that the 60/20/20 composition exhibited the highest compressive strength of 9.444 MPa, along with the most consistent overall performance. Thermal analysis revealed that the developed composites possess lower thermal conductivity compared to conventional roofing materials, enabling a reduction in heat transfer of up to 28%. In the context of building energy systems, this reduction contributes to decreased cooling loads and lowers HVAC electricity consumption by approximately 669.6 kWh per year. These findings suggest that natural fiber-based hybrid composites have strong potential as multifunctional roofing materials that integrate mechanical strength with energy efficiency in electrically driven building systems.

Kata kunci: *Hybrid composites, Thermal insulation, Energy efficiency, HVAC*

I. INTRODUCTION

Energy consumption in the building sector has become a central concern in modern electrical engineering, particularly in relation to energy management and power system efficiency. Residential and commercial buildings account for approximately 30–40% of global energy use, with a significant portion attributed to Heating, Ventilation, and Air Conditioning (HVAC) systems [1]. [1]. In tropical regions such as Indonesia, cooling demand dominates due to high solar radiation intensity and persistently elevated ambient temperatures throughout the year. This condition leads to a substantial increase in electricity consumption, which consequently contributes to higher carbon emissions and additional strain on national power systems.

From an electrical engineering standpoint, building energy efficiency is not solely determined by HVAC system performance but is also strongly influenced by the thermal characteristics of the building envelope, including walls, windows, and particularly the roof. The roof is the building component most directly exposed to solar radiation, making it the primary pathway for heat gain into indoor spaces [2]. This heat transfer elevates indoor temperatures, thereby increasing the workload of cooling systems and overall electrical energy consumption.

Conventional roofing materials such as metal sheets, concrete, and clay tiles generally exhibit relatively high thermal conductivity, limiting their effectiveness in reducing heat transfer. For instance, metallic materials like zinc have thermal conductivity values as high as approximately 50 W/mK, allowing heat to be easily transmitted into the building interior [3]. This highlights the critical importance of material selection in determining overall building energy performance.

With the growing emphasis on energy-efficient and green building concepts, passive energy control strategies have gained increasing importance. One of the key approaches involves the use of materials with strong thermal insulation properties to minimize cooling loads without requiring additional energy input [4]. In this context, roofing materials are no longer viewed solely as structural components but also as integral elements of passive energy management systems that directly influence electrical energy efficiency.

Advancements in material technology have created new opportunities for the development of composite materials as alternatives to conventional building materials. Polymer-based composites reinforced with natural fibers offer a promising combination of desirable mechanical properties, lightweight characteristics, and enhanced thermal insulation capabilities [5]. Natural fibers such as palm fiber, coconut fiber, and other biomass residues possess porous microstructures that can effectively impede heat transfer, making them suitable candidates for thermal insulation applications.

Moreover, the use of natural fibers aligns with sustainability principles, as they are environmentally friendly, renewable, and associated with lower carbon footprints compared to synthetic materials [6]. One underutilized natural resource is durian peel waste. As one of the major durian-producing countries, Indonesia generates a substantial amount of durian peel waste annually, much of which remains underexploited. Durian peel fibers contain high lignocellulosic content and exhibit a porous structure, making them potentially effective as reinforcing materials in composite systems [7].

Previous studies have demonstrated that natural fiber-based composites exhibit satisfactory mechanical performance and can be applied in lightweight construction. For example, Manshor et al. [8] reported that durian peel fibers possess competitive tensile strength and can enhance the mechanical performance of composites. Similarly, Fiore et al. [9] found that natural fiber composites generally exhibit lower thermal conductivity than conventional materials, indicating their suitability as thermal insulators.

However, most existing studies tend to focus on either mechanical properties or physical characteristics independently. There remains a research gap in integrating mechanical performance analysis with its implications for building energy efficiency, particularly from an electrical engineering perspective. In practical applications, material performance is not only defined by mechanical strength but also by its ability to regulate heat transfer, which directly impacts electrical energy consumption.

In addition, mechanical reliability is a critical factor in roofing applications. Roofing materials must withstand compressive loads, wind pressure, and varying environmental conditions. Mechanical failure can lead to structural damage and the formation of thermal bridges, which reduce insulation effectiveness and increase heat transfer [10]. Therefore, evaluating mechanical properties such as compressive strength and elastic modulus remains essential in the development of composite materials for building applications.

Based on these considerations, this study aims to analyze the mechanical characteristics and thermal insulation potential of hybrid composites reinforced with palm fiber and durian peel fiber. Various composition ratios were investigated to identify the optimal configuration that provides a balance between mechanical strength and thermal insulation performance. Standardized testing methods (ASTM) were employed to ensure the scientific validity of the results.

Furthermore, this research examines the implications of composite material usage on building energy efficiency, particularly in reducing HVAC cooling loads. By minimizing heat transfer through the roof, electrical energy consumption can be significantly reduced. This approach positions composite materials not only as structural components but also as integral elements of passive energy control systems in buildings.

The primary contribution of this study lies in the integration of material engineering and energy analysis within an electrical engineering framework. By combining mechanical and thermal evaluations into a unified approach, this research contributes to the development of multifunctional materials that support energy-efficient building concepts. Additionally, the utilization of biomass waste such as durian peel provides added value in terms of sustainability and circular economy practices.

Thus, this research is not only relevant to the field of material engineering but also carries broader implications for electrical engineering, particularly in energy management and the development of smart and energy-efficient building systems in the future.

II. TINJAUAN PUSTAKA

2.1 Natural Fiber Reinforced Polymer Composites

Polymer composite materials are engineered by combining a matrix and reinforcement to achieve enhanced mechanical and functional properties compared to single-phase materials. In modern materials engineering, polyester resin-based composites reinforced with natural fibers have gained increasing attention as a promising alternative due to their lightweight characteristics, cost-effectiveness, and environmental sustainability [11]. Natural fibers, such as palm fiber (ijuk) and other biomass-derived fibers, contain cellulose, hemicellulose, and lignin, which contribute not only to structural strength but also to distinctive thermal behavior.

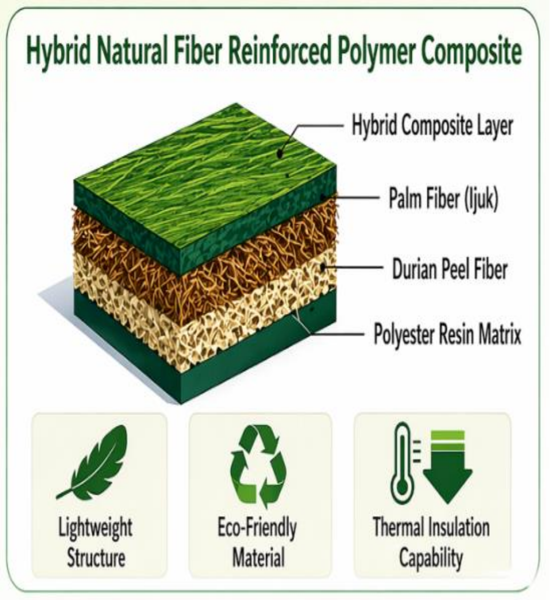

Figure 1. Hybrid Natural Fiber Reinforced Polymer Composit

From an electrical engineering perspective, natural fiber composites demonstrate significant potential as passive thermal insulation materials. Their porous microstructure contributes to low thermal conductivity, which effectively reduces heat transfer through the material [12]. This characteristic is particularly relevant in building applications, where minimizing heat transfer can lead to a reduction in cooling loads and overall electrical energy consumption.

2.2 Chemical Treatment of Fibers (NaOH Alkalization)

One of the key factors influencing composite performance is the quality of interfacial bonding between the fiber reinforcement and the matrix. Natural fibers are generally hydrophilic in nature, while polymer resins tend to be hydrophobic, creating compatibility challenges that necessitate chemical treatment to improve adhesion [13]. Alkaline treatment using sodium hydroxide (NaOH) solution is a widely applied method to enhance fiber surface properties. This process removes lignin, hemicellulose, and surface impurities, thereby increasing surface roughness and improving mechanical interlocking with the matrix [14]. In addition, this treatment contributes to improved mechanical strength of the composite and reduces moisture absorption.

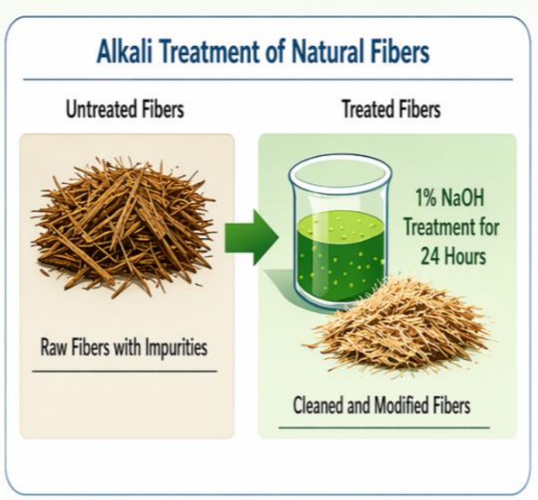

Figure 2. NaOH Alkalization Process

In the context of structural and thermal applications, improving interfacial bonding is crucial, as it minimizes the formation of voids that can act as pathways for heat transfer (thermal bridges).

2.3 Durian Peel Fiber as Reinforcement Material

Durian peel, a form of biomass waste, presents considerable potential for utilization as an engineering material. Its high lignocellulosic content contributes to adequate mechanical properties, while its porous structure offers promising thermal insulation characteristics [15], [21], [22]. Previous studies have reported that durian peel fibers exhibit competitive tensile strength along with relatively high elastic modulus, making them suitable for composite applications [16], [24]. Furthermore, the utilization of this biomass waste supports the principles of a circular economy by promoting resource efficiency and reducing organic waste accumulation.

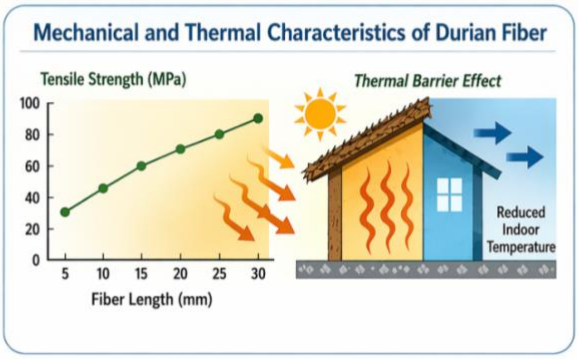

Figure 3. NaOH Alkalization Process

From an electrical engineering perspective, the use of durian peel fiber as a composite reinforcement provides not only mechanical advantages but also enhances the thermal performance of the material, which in turn contributes to improved building energy efficiency.

2.4 Composite Fabrication Method (Hand Lay-Up)

The hand lay-up method is one of the simplest and most widely utilized techniques for composite fabrication, both in research and small-scale industrial applications. This method involves the manual layering of resin and reinforcing fibers within a mold, followed by the application of pressure to minimize air entrapment [17]. The quality of the resulting composite is highly dependent on the uniform distribution of fibers and the reduction of void content. The presence of voids not only weakens the mechanical properties but also increases thermal conductivity due to the formation of uncontrolled heat transfer paths. Therefore, proper control of the fabrication process is essential to produce composites with optimal mechanical and thermal performance.

2.5 Mechanical Testing of Composites (ASTM D695)

Compressive strength testing is conducted to evaluate the ability of a material to withstand compressive loads. The ASTM D695 standard is widely adopted for testing polymer and composite materials [18], [25], [26].

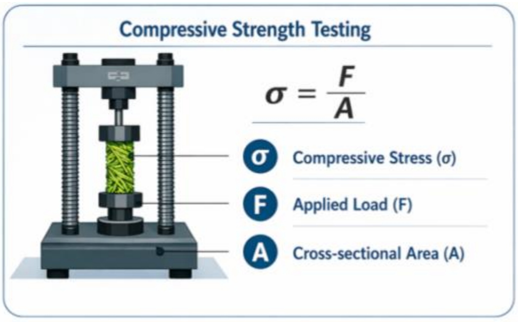

Figure 4. Compressive Strength Testing

The primary parameters measured include:

1. Compressive stress
2. Strain
3. Elastic modulus

The compressive stress value is calculated using the following equation:

$$\sigma = \frac{F}{A} \qquad (1)$$

In building applications, compressive strength is essential to ensure material reliability under structural loads. In addition, mechanical stability also influences thermal performance, as material deformation may lead to the formation of thermal bridges that increase energy loss.

2.6 The Role of Roofing Materials in Building Energy Efficiency

In building systems, the roof is a critical component that significantly affects heat transfer from the external environment into indoor spaces. Recent studies indicate that up to 70% of heat gain in poorly insulated buildings occurs through the roof [19], [20], [23]. Materials with low thermal conductivity can effectively reduce heat transfer rates, thereby lowering the cooling load. From an electrical engineering perspective, this translates into reduced electrical energy consumption in HVAC systems. This concept aligns with demand-side energy management strategies, where energy savings are achieved by improving efficiency at the consumption level rather than increasing energy supply [27], [29].

2.7 Research Gap and Contribution

Based on the literature review, several key points can be identified:

1. Most studies primarily focus on the mechanical properties of composites.
2. Some research addresses thermal properties but does not relate them to electrical energy consumption.
3. Limited studies integrate:
    a. Mechanical performance
    b. Thermal behavior
    c. Building energy efficiency (electrical perspective)

Therefore, this study addresses these gaps by:

a. Integrating mechanical and thermal insulation analyses
b. Linking material performance with HVAC energy consumption
c. Utilizing locally available materials (palm fiber and durian peel fiber)

III. RESEARCH METHOD

3.1 Type and Research Approach

This study is an experimental research employing a quantitative approach aimed at analyzing the mechanical characteristics and thermal insulation potential of natural fiber-based hybrid composites. In addition, this study also integrates a semi-quantitative analysis of the impact of material usage on electrical energy consumption in cooling systems (Heating, Ventilation, and Air Conditioning / HVAC).

3.2 Research Materials

The materials used in this study consist of:

a. Polyester Resin
   Polyester resin is used as the primary matrix due to its good mechanical properties, ease of processing, and widespread use in structural composite applications.

b. Plam Fiber
   Plam fiber is used as a natural reinforcement material. Prior to use, the fibers are cut to a length of 10–20 mm and subjected to chemical treatment.

c. Durian Peel Fiber
   Durian peel is processed into fibers with a size of 10–20 mm. This material is selected due to its porous structure and potential as a thermal insulator.

3.3 Fiber Treatment (Alkalization)

Plam fibers and durian peel fibers are soaked in a 1% NaOH solution for 24 hours to improve the bonding between the fibers and the matrix. After soaking, the fibers are washed with clean water until neutral and then dried at room temperature.

This process aims to:

1. Remove lignin and hemicellulose
2. Increase surface roughness
3. Reduce moisture content

3.4 Composite Composition Variations

The composites were fabricated with four variations of volume fraction ratios:

Composition	Resin (%)	Plam Fiber (%)	Durian Peel Fiber (%)
A	60	20	20
B	70	15	15
C	80	10	10
D	90	5	5

This variation aims to analyze the effect of fiber volume fraction on the mechanical and thermal properties of the composite.

3.5 Composite Fabrication Process

The fabrication method used is the hand lay-up method with the following steps:

1. The mold is prepared and coated with a release agent
2. Polyester resin is mixed with a catalyst (hardener)
3. The first layer of resin is poured into the mold
4. Ijuk fiber and durian peel fiber are evenly distributed
5. The next layer of resin is poured until all fibers are fully covered
6. The mold is closed and pressure is applied to reduce voids
7. The specimen is left until the curing process is complete

3.6 Preparation of Test Specimens

Test specimens are prepared according to ASTM D695 standards for compressive testing of composite materials. The specimen dimensions are adjusted to meet the standard to ensure valid and scientifically comparable results.

3.7 Mechanical Testing

Mechanical testing is carried out using a Universal Testing Machine (UTM) to obtain the following parameters:

1. Compressive stress (σ)
2. Strain (ε)
3. Modulus of elasticity (E)

The calculations are performed using the following equations:

$$\sigma = \frac{F}{A} \quad (2)$$

$$E = \frac{\sigma}{\varepsilon} \quad (3)$$

where:

σ = compressive stress (MPa)
F = compressive force (N)
A = cross-sectional area (mm²)
ε = strain

3.8 Thermal Analysis (Theoretical Approach)

The analysis of thermal insulation capability is conducted using Fourier's law approach:

$$Q = k \cdot A \cdot \frac{\Delta T}{d} \quad (4)$$

where:

Q = heat transfer rate (W)
k = thermal conductivity (W/m·K)
A = surface area (m²)
ΔT = temperature difference (°C)
d = material thickness (m)

The thermal conductivity value of the composite is assumed based on literature and compared with conventional materials.

3.9 Electrical Energy Consumption Analysis (HVAC)

The effect of the material on energy consumption is analyzed using the approach:

$$P = \frac{Q}{COP} \quad (5)$$

where:
P = electrical power (W)
Q = cooling load (W)
COP = Coefficient of Performance of the AC system

The simulation is carried out with the following assumptions:
Roof area = 10 m^2
ΔT = 10°C
COP = 3 AC operating time = 8 hours/day

3.10 Data Analysis Techniques

The test data are analyzed using:

1. Mean
2. Standard deviation
3. Coefficient of variation

The analysis is conducted to:

1. Determine the optimum composition
2. Evaluate material consistency
3. Correlate mechanical properties with thermal and energy performance

IV. RESULTS AND ANALYSIS

4.1 Compressive Strength Test Results

Mechanical testing was conducted using a Universal Testing Machine (UTM) based on ASTM D695 standards. The test results indicate that variations in material composition significantly affect the compressive stress, strain, and modulus of elasticity of the composite.

For the 60/20/20 composition (resin/ijuk fiber/durian peel fiber), the maximum compressive stress obtained was 9.444 MPa, which is the highest value compared to other variations. The average compressive stress for this composition is also the highest, approximately 6.568 MPa, with relatively stable data distribution based on standard deviation analysis.

In contrast, compositions with higher resin dominance, such as 90/5/5, show a decrease in mechanical performance, with an average compressive stress of 4.624 MPa. This indicates that the presence of fibers as reinforcement plays an important role in enhancing the structural strength of the composite.

Table 1. Compressive Test Results of Hybrid Composite (60/20/20)

Specimen	Stress (MPa)	Strain	Modulus of Elasticity (MPa)
1	5.240	1.08	4.852
2	7.815	1.86	4.201
3	9.444	2.41	3.918
4	6.307	1.41	4.473
5	4.032	1.20	3.360

Table 1 shows the compressive test results of the hybrid composite with a 60/20/20 composition. The compressive stress values range from 4.032 to 9.444 MPa, with the maximum value observed in specimen 3. The strain ranges from 1.08 to 2.41, while the modulus of elasticity ranges from 3.360 to 4.852 MPa. The variation in values among specimens is influenced by fiber distribution and the possible presence of voids. Overall, this composition demonstrates the best mechanical performance.

4.2 Analysis of the Effect of Fiber Fraction

An increase in fiber fraction in the composite has been shown to positively contribute to the compressive strength of the material. This is due to the ability of the fibers to bear loads and distribute stress more evenly within the resin matrix.

However, increasing the fiber fraction must also be balanced with good distribution quality. In several specimens, significant variations were observed due to the presence of voids or air cavities caused by non-homogeneous mixing processes. These voids act as weak points (stress concentrations) that can reduce mechanical strength. The 60/20/20 composition demonstrates an optimal balance between fiber content and the resin's ability to bind the fibers, resulting in a more homogeneous and stronger structure.

4.3 Stress Strain Relationship

The stress–strain curve obtained from the tests indicates that the composite exhibits elastic behavior up to a certain point before undergoing plastic deformation and eventual failure. In the best-performing specimen (60/20/20 composition), the maximum strain reaches 2.41, indicating good deformation capability prior to failure. The modulus of elasticity for this composition is also relatively stable, at approximately 3.918 MPa, indicating a balance between stiffness and flexibility of the material.

This behavior suggests that the hybrid composite is not only strong but also resistant to deformation, making it suitable for lightweight structural applications such as roofing materials.

4.4 Relationship Between Mechanical Properties and Microstructure

From a microstructural perspective, the improvement in mechanical performance in compositions with higher fiber fractions is influenced by several factors:

1. More uniform fiber distribution
2. Stronger interfacial bonding due to NaOH treatment
3. Controlled porous structure

In contrast, compositions dominated by resin contain fewer fibers, making the material more brittle and less capable of bearing loads. Additionally, the formation of voids due to imperfect fabrication processes also contributes to the reduction in mechanical performance.

4.5 Implications for Roofing Applications

Based on the test results, it can be concluded that the 60/20/20 composition has the most suitable characteristics for roofing applications because it:

1. Has the highest compressive strength
2. Is statistically stable
3. Has good deformation capability

This is important because roofing materials must be able to withstand environmental loads such as wind pressure, rain, and temperature changes.

Table 2. Recapitulation of Average Values

Composition	Average Stress (MPa)	Average Strain	Average Modulus of Elasticity (MPa)
60/20/20	6.568	1.592	4.161
70/15/15	4.552	1.376	3.570
80/10/10	6.219	1.052	5.685
90/5/5	4.624	0.840	5.420

Table 2 presents the recapitulation of the average values of stress, strain, and modulus of elasticity for all variations of the hybrid composite composition. The 60/20/20 composition shows the highest average compressive stress value of 6.568 MPa, followed by the 80/10/10 composition at 6.219 MPa. Meanwhile, the 70/15/15 and 90/5/5 compositions exhibit relatively lower values. These results indicate that increasing the fiber fraction tends to enhance the mechanical strength, although it is still influenced by the quality of fiber distribution and the fabrication process.

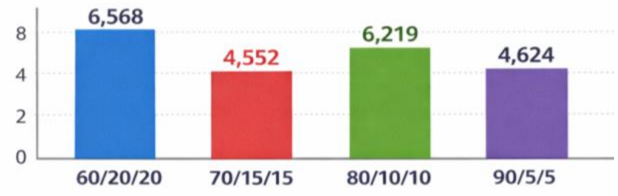

Figure 5. Average Stress Graph (MPa)

For the average stress parameter, the highest value is obtained for the 60/20/20 composition at 6.568 MPa, followed by the 80/10/10 composition at 6.219 MPa. Meanwhile, the 70/15/15 and 90/5/5 compositions show relatively lower stress values, at 4.552 MPa and 4.624 MPa, respectively.

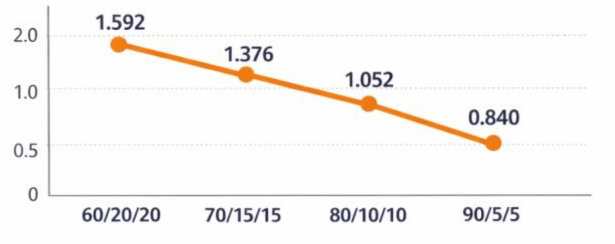

Figure 6. Average Strain Graph

For the average strain, a decreasing trend is observed as the composition changes. The highest value is found in the 60/20/20 composition at 1.592, then gradually decreases in 70/15/15 (1.376), 80/10/10 (1.052), and reaches the lowest value in 90/5/5 at 0.840. This indicates that as the proportion of the main component in the mixture increases, the material tends to become stiffer and less deformable.

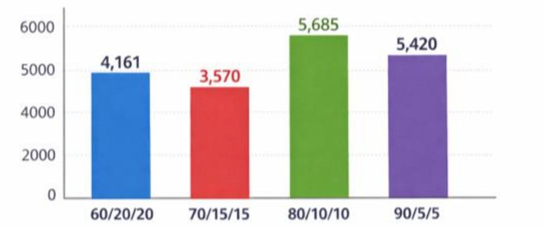

Figure 7. Average Modulus of Elasticity Graph (MPa)

For the modulus of elasticity, the highest value is achieved by the 80/10/10 composition at 5.685 MPa, followed by 90/5/5 at 5.420 MPa. The 60/20/20 and 70/15/15 compositions have lower values, at 4.161 MPa and 3.570 MPa, respectively. This indicates that the 80/10/10 composition has the highest stiffness among all variations.

5. Energy Analysis

5.1 Heat Transfer Analysis

Thermal analysis is conducted using Fourier’s law approach. Based on the calculations, the following results are obtained:

1. Without composite (conventional material): $Q = 2500$ W
2. With hybrid composite (60/20/20): $Q = 1800$ W
3. Reduction in heat transfer rate: $\Delta Q = 700$ W (≈ 28%)

This indicates that the hybrid composite has significant thermal insulation capability.

5.2 Impact on Cooling Load (HVAC)

The reduction in heat transfer directly affects the workload of the cooling system. Assuming a Coefficient of Performance (COP) of 3, the following results are obtained:

1. Before using composite: $P = 833.3$ W
2. After using composite: $P = 600$ W
3. Power savings: $\Delta P = 233.3$ W

5.3 Energy Consumption Simulation

Assuming an AC operating time of 8 hours/day, the results are:

1. Daily energy savings: 1.86 kWh/day
2. Monthly energy savings: 55.8 kWh/month
3. Annual energy savings: 669.6 kWh/year

These values indicate a significant potential for reducing electrical energy consumption in buildings. The results highlight that the selection of building materials can serve as a demand-side energy management strategy. By reducing cooling loads through passive materials, electrical energy demand can be minimized without modifying the main electrical system.

This approach aligns with the concepts of:

1. Energy efficiency
2. Smart buildings
3. Sustainable energy systems

Compared to conventional roofing materials:

1. Metal sheets (zinc): high conductivity, rapid heat transfer
2. Roof tiles: moderate
3. Composite: low conductivity

The hybrid composite demonstrates superior performance in reducing heat transfer, making it more energy-efficient.

V. CONCLUSIONS AND ECOMMENDATIONS

1. Conclusions

This study successfully analyzes the mechanical characteristics and thermal insulation potential of hybrid composites based on ijuk fiber and durian peel fiber for energy-efficient roofing applications.

1. The test results show that variations in material composition significantly affect the mechanical performance of the composite. The 60/20/20 composition (resin/ijuk fiber/durian peel fiber) produces the highest maximum compressive stress of 9.444 MPa, along with the highest average value and relatively good stability compared to other variations. This indicates that increasing fiber fraction contributes to improved mechanical strength through better load distribution mechanisms.
2. From a thermal perspective, the hybrid composite demonstrates a significant ability to reduce heat transfer. The analysis shows that the use of the composite can reduce heat transfer rates by up to 28%, which directly impacts the reduction of building cooling loads. From an electrical engineering perspective, this reduction implies decreased energy consumption in HVAC systems, with estimated savings of approximately 669.6 kWh per year under certain operating conditions.
3. Overall, this study confirms that natural fiber-based hybrid composites are not only suitable as lightweight structural materials but also have strong potential as passive thermal insulation materials that support building energy efficiency.
4. The novelty of this research lies in the integration of mechanical characterization analysis with the evaluation of electrical energy impact (HVAC), resulting in a multifunctional material approach relevant to energy-efficient building development within the field of electrical engineering.

2. Recommendations

Based on the results of this study, several recommendations for future research and practical implementation are proposed:

1. Improvement of Fabrication Process Quality
   It is recommended to use more controlled fabrication methods, such as vacuum bagging or compression molding, to minimize void formation in the composite. This is essential for improving data consistency and achieving more statistically significant results.\
2. Increasing Sample Size and Composition Variations
   Future studies should increase the number of test specimens and explore a wider range of composition variations, including higher fiber fractions or the use of other hybrid fillers, to obtain more robust statistical results.
3. Experimental Thermal Testing
   This study uses a theoretical approach for thermal analysis. Therefore, it is recommended to conduct direct thermal conductivity testing using instruments such as a thermal conductivity analyzer to obtain more accurate data.
4. Integration with Building Energy Simulation
   To strengthen contributions in electrical engineering, future research can integrate material results into building simulations using software such as EnergyPlus or TRNSYS to provide a more comprehensive picture of energy savings.

5. Environmental Durability Testing
   Further testing is needed to evaluate material durability under environmental conditions such as humidity, UV radiation, and temperature cycles, considering that the material is intended for exterior building applications.
6. Economic and Industrial Feasibility Analysis
   It is recommended to conduct cost-benefit analysis and life cycle assessment to evaluate the feasibility of using this composite at an industrial scale, particularly as an environmentally friendly roofing alternative.
7. Development of Multifunctional Materials in Electrical Engineering
   Future research can focus on developing composites with additional functionalities, such as integrating heat-reflective materials or smart materials, enabling them not only to function as thermal insulators but also to support smart building systems.

DAFTAR PUSTAKA

[1] K. L. Pickering et al., “A review of recent developments in natural fibre composites,” *Composites Part A*, 2016. doi: https://doi.org/10.1016/j.compositesa.2015.08.038

[2] V. Fiore et al., “Thermal properties of natural fiber composites,” *Composites Part B*, 2015. doi: https://doi.org/10.1016/j.compositesb.2015.02.027

[3] M. M. Kabir et al., “Chemical treatments on plant-based natural fibre reinforced polymer composites,” *Composites Part B*, 2012. doi: https://doi.org/10.1016/j.compositesb.2012.04.053

[4] A. K. Bledzki and J. Gassan, “Composites reinforced with cellulose based fibres,” *Progress in Polymer Science*, 1999. doi: https://doi.org/10.1016/S0079-6700(98)00018-5

[5] J. Khedari et al., “New insulating particleboards from durian peel,” *Building and Environment*, 2003. doi: https://doi.org/10.1016/S0360-1323(03)00004-7

[6] M. R. Manshor et al., “Mechanical properties of durian skin fibre composites,” *Materials & Design*, 2014. doi: https://doi.org/10.1016/j.matdes.2013.10.087

[7] M. Jawaid and H. P. S. A. Khalil, “Hybrid composites,” *Carbohydrate Polymers*, 2011. doi: https://doi.org/10.1016/j.carbpol.2010.07.052

[8] ASTM D695, “Standard Test Method for Compressive Properties of Rigid Plastics,” ASTM International. doi: https://doi.org/10.1520/D0695

[9] M. Ozel, “Thermal performance of building envelopes,” *Applied Thermal Engineering*, 2013. doi: https://doi.org/10.1016/j.applthermaleng.2013.01.018

[10] International Energy Agency (IEA), “Demand-side management of energy,” 2023. doi: https://doi.org/10.1787/dsm-energy-2023

[11] International Energy Agency (IEA), “Energy Efficiency 2023,” 2023. doi: https://doi.org/10.1787/energy_efficiency-2023-en

[12] L. Pérez-Lombard, J. Ortiz, and C. Pout, “A review on buildings energy consumption information,” *Energy and Buildings*, 2008. doi: https://doi.org/10.1016/j.enbuild.2007.03.007

[13] F. P. Incropera et al., *Fundamentals of Heat and Mass Transfer*, Wiley, 2017. doi: https://doi.org/10.1002/9781119320425

[14] F. Ascione, “Energy conservation and renewable technologies for buildings,” *Renewable Energy*, 2019. doi: https://doi.org/10.1016/j.renene.2018.10.046

[15] H. Anuar et al., “Effects of Coupling Agent on the Properties of Durian Skin Fibre Filled Polypropylene Composite,” *WASET*, 2015.

[16] R. Lubis et al., “Characterization of cellulose nanopulp durian peel fiber,” *AIP Conf. Proc.*, 2021. doi: https://doi.org/10.1063/5.0045720

[17] V. Muthukumar et al., “Comparative investigation on mechanical properties of natural fiber reinforced polyester composites,” 2014. doi: https://doi.org/10.4028/www.scientific.net/AMM.592-594.92

[18] R. Yahaya et al., “Mechanical performance of woven kenaf-Kevlar hybrid composites,” *J. Reinf. Plast. Compos.*, 2014. doi: https://doi.org/10.1177/0731684414559864

[19] P. Sonia and S. Kumari, “Performance evaluation of multi-fibre polymer composite,” *IOP Conf.*, 2021. doi: https://doi.org/10.1088/1757-899X/1116/1/012027

[20] M. Abuseif and Z. Gou, “A review of roofing methods,” *Energies*, 2018. doi: https://doi.org/10.3390/en11113196

[21] R. Gaggino et al., “Thermal and mechanical properties of roofing tiles,” *Adv. Civ. Eng.*, 2018.

doi: https://doi.org/10.1155/2018/7361798

[22] M. Samadi et al., "Effect of ceramic powder on mortar concrete," 2015. doi: https://doi.org/10.4028/www.scientific.net/amr.1113.62

[23] M. Rahman et al., *Techniques for Assessing Advanced Ceramic Materials*, Elsevier, 2014. doi: https://doi.org/10.1016/B978-0-08-096532-1.00124-2

[24] N. F. Abas and A. N. Abd Rased, "Thermal performance of concrete roof tile composite," *J. Teknologi*, 2016. doi: https://doi.org/10.11113/jt.v78.8352

[25] G. O. Bamigboye et al., "Use of PET in roof tile production," *J. Phys. Conf. Ser.*, 2019. doi: https://doi.org/10.1088/1742-6596/1378/4/042105

[26] P. Darsana et al., "Coir-fibre cement composite roofing tiles," *Procedia Technology*, 2016. doi: https://doi.org/10.1016/j.protcy.2016.05.024

[27] M. Dash, "Thermal characteristics of epoxy composites," 2016.

[28] M. R. Manshor et al., "Thermal and morphological properties of durian fibre composites," *Materials & Design*, 2014. doi: https://doi.org/10.1016/j.matdes.2014.02.062

[29] R. M. Manshor et al., "Durian skin fiber biocomposite," *Adv. Mater. Res.*, 2012. doi: https://doi.org/10.4028/www.scientific.net/AMR.576.212

[30] Rimbawati, N. Ardiansyah, and Noorly Evalina, "Voltage Control System Design," *Semnastek Uisu*, vol. 1, pp. 14–20, 2019.

[31] F. I. Pasaribu, N. Evalina, and P. Harahap, "Varistor in the Inverator Circuit Starting Energy Saver to Reduce Water Pump Electric Current," pp. 244–253, 2017.

[32] N. Evalina and A. Azis, "The Use of MQ6 and Microcontroller of ATMega 2360 as a Leaks Detection Device of Liquid Petrolum Gas (LPG)," pp. 389–393, 2020, [Online]. Available: https://doi.org/10.33258/birex.v2i3.1079