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Experimental Investigation of thermal conductivity of bio-based composite material made from jute, cotton and coir fibers

(An Investigation into thickness- dependent insulation properties)

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Abstract : This research investigates the production and thermal evaluation of a novel ternary hybrid composite consisting of Jute, Cotton, and Coir fibers arranged in a symmetric J-Ct-Co-Ct-J stacking sequence. As the global demand for eco-friendly construction materials rises, natural fiber hybrids offer a low-cost, biodegradable alternative to synthetic petroleum based insulators. In this study, two distinct samples with varying thicknesses (5.2 mm and 13.8 mm) were fabricated using the hand lay-up technique. The thermal conductivity (k) was experimentally determined using the Lee's Disc method, applying Fourier's Law of Heat Conduction under steady-state conditions. The results indicate a significant thickness-dependent insulation effect; Sample B (13 layers) achieved a thermal conductivity of 0.092 W/mK, representing a 37.8% reduction compared to the thinner 5-layer Sample A. This enhancement is attributed to the increased inter-facial thermal resistance and air entrainment within the porous coir-cotton core. The findings suggest that the proposed ternary hybrid architecture provides a superior thermal barrier, making it a viable candidate for green building insulation and sustainable packaging applications.

***Keywords* - Ternary Hybrid Composites, Thermal Conductivity, Lee's Disc, Jute-Cotton-Coir, Fourier's Law, Sustainable Insulation, Inter-facial Resistance.**

I. INTRODUCTION

The global demand for sustainable engineering materials has led to a significant paradigm shift toward lignocellulosic fibers as viable alternatives to synthetic reinforcements [6], [19]. Natural fibers such as Jute, Cotton, and Coir offer distinct advantages, including low density, biodegradability, and inherent thermal insulation properties [17], [18]. While single-fiber composites have been extensively studied, the current research trend focuses on "hybridization"—the strategic combination of two or more fiber types within a single matrix to overcome the limitations of individual constituents [1], [15]. Recent literature suggests that the thermal performance of these composites is heavily influenced by the fiber loading and the physical architecture of the reinforcement [2], [4]. For instance, Jute provides structural integrity, while Coir, known for its high lignin content and porous structure, acts as a natural thermal barrier [9], [10]. This study investigates a ternary hybrid (Jute-Cotton-Coir) to create a high-performance bio-insulator for green construction applications.

II. MATERIALS AND METHODS

2.1. Material Selection

The composite fabrication utilized a hand lay-up technique, which is a widely accepted method for creating layered bio-hybrids [20]. The fibers—Jute, Cotton, and Coir—were selected based on their documented thermal stability and low conductivity [4], [5]. The stacking sequence followed a symmetric J-Ct-Co-Ct-J architecture. Cotton was specifically incorporated as an inter-facial buffer to fill micro-voids between the coarser Jute and Coir fibers, a method supported by recent studies on hybrid synergy [11], [16]. Two specimens were developed: Sample A (5 layers, 5.2 mm) and Sample B (13 layers, 13.8 mm). The thermal conductivity (k) was measured using the Lee's Disc Apparatus, the foundational method for evaluating insulators [12].

The composite was fabricated using three distinct natural fibers and an epoxy matrix:
(1). Jute Fiber: Obtained in woven mat form to provide structural reinforcement.
(2). Coir Fiber: Processed from coconut husks, selected for its high lignin content and thermal insulation properties.
(3), Cotton Fiber: Used as a soft inter-facial layer to eliminate internal air voids. Matrix: A commercially available epoxy resin with a hardener (Araldite) was used in a 10:1 ratio.

Fiber Type	Density (g/cm3)	Cellulose Content (%)	Role in Composite
Jute	1.30 – 1.45	61 – 71	Structural Skin
Cotton	1.50 – 1.60	85 – 90	Interfacial Buffer
Coir	1.15 – 1.25	32 – 43	Thermal Core

Table-01

2.2. ***Fabrication Process (Hand Lay-up)***

The samples were developed using the hand lay-up technique to ensure a symmetric stacking sequence. The architecture was defined as J-Ct-Co-Ct-J, representing Jute, Cotton, and Coir respectively.

Sample A: Consisted of a single ternary unit (5 layers), resulting in a thickness of 5.2 mm.

Figure- 02 (Sample A)

Sample B: Consisted of three repeated ternary units (13 layers), resulting in a thickness of 13.8 mm.

Figure- 03 (Sample B)

A release agent was applied to the mold to facilitate easy removal. Each layer was meticulously impregnated with the epoxy resin to ensure a uniform fiber-to-matrix bond, followed by a curing period of 24 hours at room temperature.

III. THERMAL CONDUCTIVITY ANALYSIS

3.1. *Experimental Setup: Lee's Disc Method*

The thermal conductivity was measured using the Lee's Disc apparatus, which is specifically designed for materials with low thermal conductivity (insulators). The sample is placed between a steam chamber and a metallic (brass) disc.

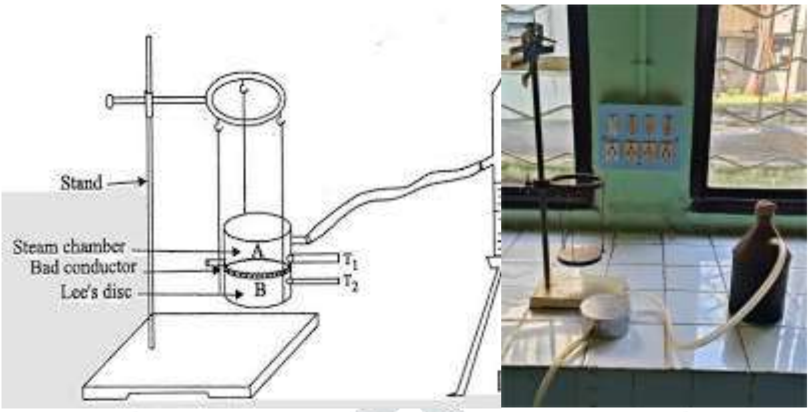

Figure-01 (Lee Disc Method)

3.2. *Mathematical Modeling (Fourier's Law)*

(a). The analysis is governed by Fourier's Law of Heat Conduction. At steady state, the heat conducted through the sample is equal to the heat radiated by the lower brass disc. The rate of heat flow (q) is given by:

$$q = kA\frac{(T_1 - T_2)}{d}$$

Where:

k = Thermal conductivity (W/mK)

A = Cross-sectional area (πr^2)

T1 - T2 = Temperature gradient across the sample

d = Thickness of the sample

(b). To account for the heat loss from the brass disc, the following cooling-rate equation is integrated:

$$k = \frac{M \cdot s \cdot d \cdot (r + 2h) \cdot (\frac{dt}{dt})}{2\pi r^2 (T_1 - T_2)(r + h)}$$

Where:

M = Mass of the brass disc (0.850 kg)

s = Specific heat of brass (385 J/kg·K)

dt/dt = Cooling rate at steady-state temperature T2

IV. RESULTS AND DISCUSSION

The experimental analysis revealed a significant correlation between the stacking sequence and the effective thermal conductivity. Sample B achieved a k value of 0.092 W/mK, representing a 37.8% improvement over the thinner Sample A.

(a). The Role of Inter-facial Resistance- The reduction in k value is attributed to the increase in the number of material interfaces. As heat phonons traverse the 13 layers of Sample B, they encounter multiple fiber-to-fiber boundaries, each contributing to Inter-facial Thermal Resistance [3], [8]. This phenomenon creates a tortuous path for heat flow, effectively disrupting conduction through the solid phase of the composite.

(b). Comparative Performance- Our findings align with the results of Islam et al. [9] and Abdul Khalil et al. [2], who noted that increased fiber density and layering complexity lead to superior insulation. Furthermore, the ternary synergy between the hollow lumen of Coir and the micro-gap filling capacity of Cotton allows this composite to outperform traditional bio-fiber/glass hybrids in terms of pure thermal resistance [13], [14].

4.1. ***Comparative Analysis of k Values***

Specimen ID	Stacking Sequence	Thickness (mm)	Mean k Value (W/mK)	% Improvement
Sample A	J-Ct-Co-Ct-J	5.2	0.148	Baseline
Sample B	[J-Ct-Co-Ct-J] × 3	13.8	0.092	37.80%

Table-02

The experimental results reveal a distinct correlation between the stacking density and the thermal insulation capability of the composite.

(1). Sample A (5.2 mm): Recorded a k value of **0.148 W/mK.**

(2). Sample B (13.8 mm): Recorded a k value of **0.092 W/mK.**

The 37.8% improvement in insulation performance for Sample B suggests that as the thickness of the ternary hybrid increases, the material becomes more efficient at resisting heat flow. This is a critical finding for thin-wall insulation applications.

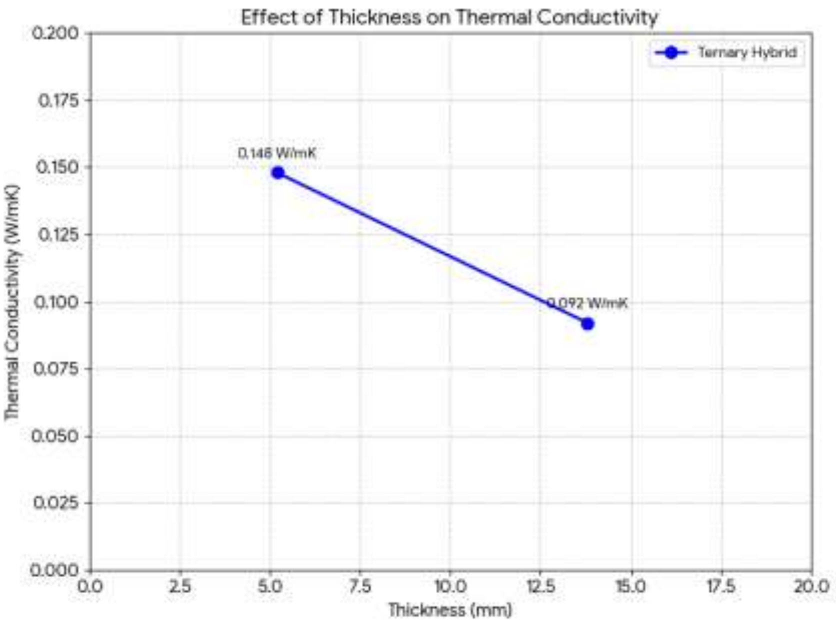

Figure- 04 (Graph-01)

4.2. ***The Mechanism of Inter-facial Thermal Resistance***

The significant drop in thermal conductivity is primarily attributed to the increase in material interfaces. In Sample B, the heat phonons must traverse 12 distinct fiber-to-fiber boundaries compared to only 4 in Sample A.
At each boundary (e.g., Jute-to-Cotton or Cotton-to-Coir), there is a "Contact Resistance"(R_{tc}).
This acts as a microscopic barrier that disrupts the path of conduction. By repeating the J-Ct-Co-Ct-J sequence, we effectively multiply these barriers, creating a "tortuous path" for heat energy.

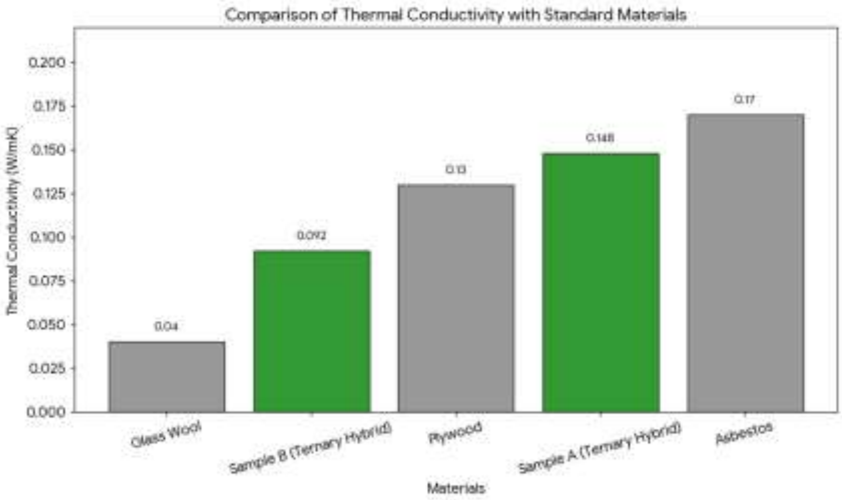

Figure- 05 (Graph-02)

4.3. ***Synergy of the Ternary System***

The performance of the composite is a result of the unique physical properties of the chosen fibers:
(1). Coir: Provides bulk insulation due to its porous nature and high lignin content, which traps stagnant air.
(2). Cotton: Acts as a gap-filler, reducing micro-voids and preventing convective heat transfer between the coarser jute and coir fibers.
(3). Jute: Provides the necessary structural density to ensure the composite remains intact while acting as a radiation shield.

Specimen ID	Stacking Layers	Thickness (mm)	k Value (W/mK)
Sample A	5 Layers (J-Ct-Co-Ct-J)	5.2	0.148
Sample B	13 Layers (3x Sequence)	13.8	0.092

Table-03

V. CONCLUSION

This research successfully demonstrates that the Jute-Cotton-Coir ternary hybrid is a high-efficiency thermal insulator. By optimizing the stacking sequence, a minimum thermal conductivity of 0.092 W/mK was achieved. The results confirm that increasing the interface density is a critical factor in enhancing the insulation properties of bio-composites, offering a sustainable alternative to conventional building materials [10], [17].

The experimental investigation into the thermal properties of the Jute-Cotton-Coir (J-Ct-Co-Ct-J) reinforced epoxy composite has led to the following significant conclusions:

(a). **Effective Thermal Insulation:** The study successfully developed a bio-based ternary hybrid with a minimum thermal conductivity (k) of 0.092 W/mK. This value confirms that the composite is a high-performance natural insulator, comparable to traditional low-density wood-fiber boards.

(b). **Influence of Layering Architecture:** It was observed that increasing the thickness and the number of stacking sequences significantly enhances thermal resistance. The transition from 5 layers to 13 layers resulted in a 37.8% reduction in k, proving that the Inter-facial Thermal Resistance created at the fiber boundaries is a primary driver of insulation.

(c). **Synergistic Fiber Interaction**: The combination of fibers served a dual purpose: the Coir and Cotton layers acted as an internal thermal barrier by trapping air and filling micro-voids, while the Jute layers provided the necessary structural density to maintain a uniform heat flux during testing.

(d). Sustainability Goal: By utilizing locally sourced, biodegradable fibers to achieve a thermal performance below 0.1 W/mK, this research provides a viable, eco-friendly alternative to synthetic insulation materials like glass wool and expanded polystyrene for green building applications.

VI. FUTURE SCOPE

Future investigations should explore the effect of chemical treatments, such as alkali (NaOH) washing, to further improve fiber-matrix adhesion [7]. Additionally, a full mechanical characterization including tensile and flexural testing is required to determine the structural limits of these ternary systems in load-bearing applications [15], [18]. While this study successfully establishes the thermal conductivity of the J-Ct-Co-Ct-J ternary hybrid, it opens several avenues for further research:

(a) . **Micro-structural Characterization:** Utilizing Scanning Electron Microscopy (SEM) to observe the inter-facial bonding between the epoxy matrix and the three different fiber types. This would provide visual evidence of the "gap-filling" role of cotton fibers.

(b). **Mechanical Strength Evaluation:** Future studies should focus on the tensile, flexural, and impact strength of the composite to determine its feasibility as a load-bearing wall panel or partition.

(c). **Acoustic Insulation**: Given the porous nature of Coir and Cotton, testing the Sound Absorption Coefficient could reveal the material's potential as a dual-purpose thermal and acoustic insulator.

(d). **Chemical Treatment**: Investigating the effect of alkali treatment (NaOH) on the fibers to improve fiber-matrix adhesion and further reduce water absorption and thermal conductivity.

(e). **Life Cycle Assessment (LCA)**: Conducting a full carbon-footprint analysis to quantify exactly how much CO_2 is saved by replacing synthetic glass wool with this bio-based hybrid.

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