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Influence of Static Sequences on the Thermal Behavior of Eco-Friendly Pineapple/Ramie Composites

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Abstract

The increasing demand for sustainable and environmentally responsible materials has driven the exploration of natural fiber-reinforced polymer composites as potential alternatives to conventional synthetic materials. Among various natural fibers, pineapple leaf fiber (PALF) and ramie fiber are notable for their complementary characteristics—PALF offers excellent insulating behavior and lightweight structure, while ramie provides high thermal stability and strength. In the field of Eco-friendly composite product manufacturing, the processing temperature holds significant relevance in influencing overall performance. Therefore, the relevant aspects of the thermal properties of composites must be considered, and accurate thermal measurements using composite test methods are necessary. In this study investigates the thermal properties of six composite specimens with different stacking sequences. The specimens were evaluated based on thermal conductivity (CT), heat deflection temperature (HDT), and coefficient of thermal expansion (CTE). Results indicate that stacking sequences PRRPRRP exhibits the highest thermal conductivity (0.345 W/mK), while RPRPRPR has the lowest (0.205 W/mK). The highest HDT (250°C) was observed in stacking sequences PPRRRPP and RPRPRPR, suggesting superior thermal stability. Conversely, stacking sequences RPPRPPR demonstrated the lowest HDT (87.8°C). The coefficient of thermal expansion varied significantly, with stacking sequences RPPRPPR having the lowest CTE (1×10^{-6} /°C), indicating minimal dimensional changes under thermal stress, while RPRPRPR showed the highest CTE (2×10^{-5}/°C). Overall, the study emphasizes that static stacking sequence plays a crucial role in determining the thermal characteristics of natural fiber composites. These findings highlight the influence of stacking sequence on thermal behavior, providing insights for optimizing composite materials in high-temperature applications, particularly eco-friendly composites for use in construction, automotive, and thermal barrier systems.

Keywords: ramie fiber; Pineapple fiber; ply; thermal expansion; heat, epoxy

INTRODUCTION

Natural plant fibers like coconuts, bananas, and bamboo have become popular in the production of the fiber-reinforced hybrid composites Laminates. The hybrid composites Laminates are more demanded compared to synthetic fibers because of their superior properties [1]. Hybrid composite are expected to replace plastics in the future, with mechanical properties evaluation techniques such as tensile, impact, flexural and dynamic analysis [2]. Examined the hybrid composites made from woven ramie fiber mats, epoxy resin, and sponge iron slag, demonstrating industrial waste can be utilized to improve mechanical properties [3]. The need for biodegradable composites and the advantages of using natural fibers, including their lightweight and cost-effectiveness. The research

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involved seven different arrangements, including layers of basalt and ramie fabric, with experimental tests aimed at evaluating their mechanical properties [4]. Pineapple and ramie fiber composites are typically made through processes like hand lay-up, compression molding, resin transfer molding, vacuum bagging. Hand lay-up is most extensively utilized due to its ease of use and low cost, which is best for tailoring fiber stacking sequences. Compression molding and hot pressing yield improved mechanical and thermal properties through strong fiber-resin bonding. Vacuum bagging provide accuracy and better quality, appropriate for higher-level applications. [5]. Mixed fiber reinforced composites provide substantial enhancements compared to using single fibers in various applications such as textiles, insulation, and heat-resistant plates. By harnessing the collective advantages of multiple fibers, these composites offer superior performance and greater versatility [6]. Researchers conducted a comprehensive investigation into the applications of glass fiber, carbon fiber and flax fiber, in reinforcing polymers. The study reveals that the unveiled that Hybrid composite made from flax fibers exhibit exceptional mechanical characteristics and possess a greater ability to absorb vibrations. By combining flax with carbon fibers in a common matrix, the total mechanical behaviors of hybrid green composites may be enhanced further. Important degradation mechanisms noted during the research included matrix cracking, embryology, deboning, and fiber breakage [7-8]. Novel composite laminates are developed by altering fiber arrangement and reinforcement material weight percentages for comprehensive investigation [9]. Extensive research has been conducted on basalt fibers, which are obtained from volcanic rocks found in nature. These volcanic rocks possess finely grained fibers, typically measuring between 10 and 20 micrometers in width [10]. This paper investigated the characteristics of composites, specifically focusing on their vibration and material properties. Through their research, they discovered that the residual bending strength of these composites undergoes a noteworthy enhancement when exposed to a temperature of 75°C. However, this strength diminishes when the temperature rises further to 90°C temperature, which is in close proximity to the glass transitions temperature [11]. Composites made using various methods, including the wet layup method, showed comparable performance [12]. The study examined tensile

Mechanical behavior of a composite material made up of basalt fiber-reinforced polymer. To show the distortion distributions, a method referred to as digital image correlation (DIC) was utilized. It was found that the composite material showed non-homogeneous patterns, and strain responses were estimated and correlated to applied stresses. The analysis focuses on the challenge in describing mechanical properties at varied strain rates [13-14]. The composite material's properties are determined by fiber alignment, with unidirectional arranged Manila hemp fibers and epoxy resin/poly-lactic acid reducing thermal conductance by 33.33% but increasing weight fraction by 40–69% [15]. Composite materials are widely favored for their outstanding characteristics and diverse range of uses. However, effectively describing these materials poses a challenge due to factors such as their environmental impact, the uncertainty surrounding fiber properties, insufficient adhesion, and the absence of timely material failure indicators [16]. The focus examined the thermal and mechanical characterization of steam-exploded kigelia pinnata fruit fibers reinforced with vinyl ester polymers and treated with silane grafting, revealing enhanced interfacial bonding [17-18]. Due to their high thermal conductivity, excellent elongation, and low density, basalt fibers, which are obtained from volcanic rocks with small grains, are utilized in textiles, heat-resistant plates, and building insulation [19]. The study reveals that the addition of fishbone nanofiller and Phoenix pusilla dry leaves to hybrid composites enhances their tensile, flexural, and hardness properties [20]. Sayyidmousavi et al [21]. This study investigated on thermal conductance (CT) of a hybrid polymer composite using hemp fibre as the polymer matrix and reinforcement [22]. Hybrid composite goods can be made using a variety of methods, including melt compression, extrusion, and injection molding [23]. Plant fibers are sustainable materials, but their hydrophilicity limits compatibility with polymers. Eco-friendly surface treatments now offer a greener alternative to traditional chemical methods for improving fiber-matrix bonding [24]. *Citrus x sinensis* peel waste was used to extract cellulose with a 67.82% yield. The purified cellulose showed good crystallinity, thermal stability, and surface properties, making it suitable as a reinforcing material in polymer composites [25]. *Phormium tenax* fibers were added to natural rubber to enhance its properties.

The 6 mm fibers gave the best balance of strength, hardness, and abrasion resistance, with performance improving as fiber content increased [26]. *Acacia caesia* bark fibers improved the mechanical and thermal properties of epoxy composites, with 20 mm fibers showing the best performance and strong fiber-matrix bonding [27]. *Alkali-treated areca and glass fibers in an epoxy matrix improved tensile, flexural, and impact strengths, with reduced wear loss and better fiber-matrix adhesion at higher fiber loadings* [28].

The above literature review highlights a significant amount of research studies that have looked into the thermal and morphological characterizing of polymer composite materials consisting of Eco-Friendly natural fibers. A majority of studies emphasize composite laminates where the layers consist of single fibers. Based on the literature, it has been found that the use of more than one fiber in composite more Advantages compared to composite using a single fiber. Because they are more cost-effective and environmentally friendly, natural fibers are being utilized more often as reinforcements in polymer composites. Furthermore the literature review is to explore how the orientation of pineapple and ramie fibres in hybrid composites affects their thermal characteristics Such as heat deflection, linear thermal expansion coefficient, and thermal conductivity. To conduct further research, a scanning electron microscope (SEM) was utilized to determine the composite fracture as a hybrid composite laminates.

MATERIALS AND METHODS

Materials

The reinforcements used in this study are mats in ramie and pineapple fibers. For creating the cohesiveness, mats are subjected to pressing and chemical bonding for consolidating their structure. Then the fiber mats are subsequently precisely cut to the size (300mm*300mm) as required for the measurement. These fiber mats are then combined with a polymer matrix material to create composite laminates, employing the utilization of a vacuum bagging machine.

Table 1 shows lists of the various mechanical properties of Pineapple, ramie, and matrix polyester fibres [29-30]. Epoxy resin and hardener from Javanthee enterprises in Chennai, India, are used in this study to create pure and hybrid composite laminates. The resin is bifunctional, and aliphatic primary amines like LY556 and HY951 are used as the hardener. It is common practice to premix and homogenise the epoxy and mix it with the hardener in a 10:1 weight ratio.

Table 1. Physical characteristics of Materials'

SL No	Name of the Fibers	Strength (MPa) of the fibers	Modulus Elasticity (GPa) of the fibers	Density (g/m3) of the fibers	Poisson's Ratio of the fibers	Type of fabrics
1	Pineapple (P)	300–430	110	2.8	0.24	Woven
2	Ramie (R)	170–200	80	1.2	0.2	Woven
3	polyester	35-40	3	1.09	0.23	Resin

Composite Laminate Preparation

The process of fabricating a composite laminate made of pineapple, ramie, and epoxy is showed in Figure 1. To improve their cohesion, the mats are submitted to chemical bonding and pressed to stabilize their structure. The fiber mats are then cut to precise (300mm*300mm) dimensions for measuring purposes Next, we arrangement as per static sequence them according to the composite order as follows Table.2 furthermore by utilizing the vacuum bag infusion technology was used to make the green polymer composite with different stacking sequences of pineapple/rami reinforcement [31]. The surface under the vacuum bag infusion setup was glass with an output agent. The samples were sealed with sealant tape and covered with plastic cover to avoid leakage. A vacuum pump was attached to one end of the corner, it was used to pull out extra resin to be remove the mold. Once placed at a temperature of 2.040 kg / cm2 for 8 to 10 minutes, the composite laminate was dried and opened in a wet to dry method using warm air. The laminate was then cured for 24 hours and kept at a weight of 25.00 kg.According to ASTM standards dimensions were prepared used water jet machine pineapple/ ramie composite laminates. This study's hybrid composites' overall fiber volume fraction and the contribution of each fiber batch percent to the total fiber volume fraction are shown in Table 2. To get the fiber volume %, the formula is given in equation (1). In order to calculate the fiber volume %, the density of the reinforcing fibers utilized in this investigation is given in Table 1.were named the sequence for sample code as follow S1-BBRRBB; S2-RRPRR; S3-BRPRPRP; S4-RBBRBRBR; S5-PRPRPRPRP; S6-RBRBRBR.The arrangement of fiber layers static sequences plays a key role in balancing thermal insulation and thermal stability, insulation performance, and resistance to degradation of fiber-reinforced composites. The sequence of ramie and pineapple fibers in stacking has a major influence on the thermal behavior of composite materials. Pineapple-based sequences enhance thermal stability with an HDT of as much as 250°C, Ramie-dominated layers amplify thermal insulation with lower thermal conductivity (0.205 W/mK), courtesy of the lower density of ramie.Alternating ramie and pineapple fibers stacking sequences also enable improved dimensional stability with reduced thermal expansion for reliability under conditions of temperature fluctuation. In general, precise design of the stacking sequences enables customized thermal properties for specific performance requirements in high-temperature or insulating applicati

$$Vf = (Wb/ \rho b) + (Wr/ \rho r)/((Wb/ \rho b) + (Wr/ \rho r) + (Wm/ \rho m)) \tag{1}$$

Table 2. Stacking sequence of composites.

Sl No	Sequence and Sample Code	Laminate Thickness (mm)	Weight(g)				Fiber Volume Fraction of Basalt Fiber, bf (%)	Fiber Volume Fraction of Ramie, Rf (%)	Total Fiber Volume Fraction, Vf (%)	Matrix Volume Fraction, Vm (%)
			Weight of Composite (Wc)	*Weight of Basalt (Wb)*	*Weight of Ramie (Wr)*	*Weight of Matrix (Wm)*				
1	PPRRRPP(S1)	2.85	23.40	5.286	3.820	7.82	24.56	18.69	43.56	56.56
2	RRPPPRR(S2)	3.27	24.01	4.783	2.869	8.69	22.68	20.23	45.00	50.28
3	PRRPRRP(S3)	3.02	19.50	4.123	3.082	6.98	25.00	16.89	42.38	51.28
4	RPPRPPR(S4)	3.56	23.08	5.896	3.526	8.01	18.98	17.89	44.85	49.36
5	PRPRPRP(S5)	3.70	24.86	4.963	3.762	7.92	20.36	19.85	41.03	47.98
6	RPRPRPR(S6)	3.01	22.90	3.986	3.685	6.98	21.98	16.36	44.85	50.98

RESULTS AND DISCUSSIONS

Thermal conductance

Figure 2 Provides an illustration of the hybrid composite's thermal conductance. The sample code "S3" was found to have a maximum thermal conductivity (CT) of 0.345 W/mK in all hybrid composites prepared using ramie fibers connected by pineapple fibers. The outer layers of the pineapple fibers then switched this. The thermal conductivity (CT) of hybrid composite "S1" was 1.15% lower than that of "S3". The system had a sandwich-like arrangement of rami fibers in a dual configuration, with the middle part consisting of three layers of pineapple fibers. The thermal conductivity of hybrid green mixed sampling code "S4" was 1.24% lower than that of the sample Code "S2"was obtain minimum thermal conductivity (TC) of 0.205W/mK, the model code 'S6' is the worst performing hybrid composite. The heat transfer capability of hybrid composites is reduced when pineapple fibers are combined with ramie fibers, facilitating the composites' construction. Pineapple fibers have higher strength (300–430 MPa), modulus of elasticity (110 GPa), and density (2.8 g/cm³). These attributes result in greater thermal conductivity and higher heat deflection temperatures, making them suitable for high-temperature applications. For example, composite S1 (PPRRRPP) shows HDT = 250°C and thermal conductivity = 0.302 W/mK. The Ramie fibers, with moderate strength (170–200 MPa) and lower density (1.2 g/cm³), contribute to lower thermal conductivity and better insulation properties. However, they also lead to lower heat resistance, as seen in S2 (RRPPPRR) with HDT = 96.8°C and thermal conductivity = 0.216 W/mK.

Coefficient of linear thermal expansion

Figure 3 Illustrates the variation in Coefficient of linear thermal expansion (CLTE) for different composite specimens with six different stacking sequences. The Coefficient of linear thermal expansion (CLTE) (300 °C to 600 °C) for hybrid composites.

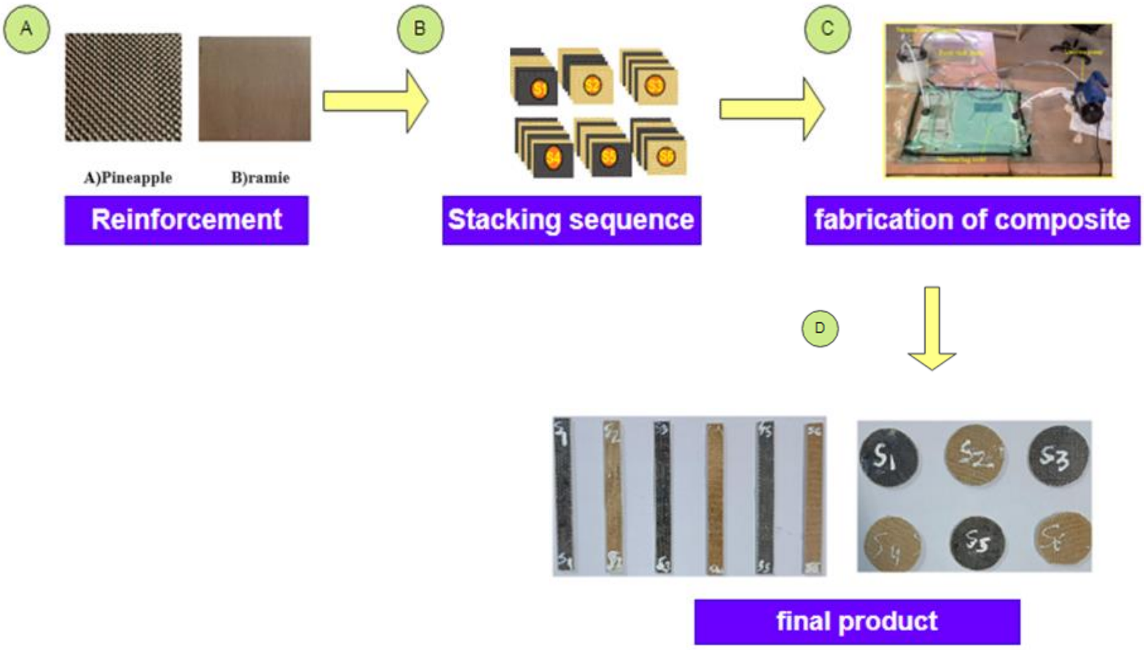


Figure 1. Manufacturing process for Composite Laminate.

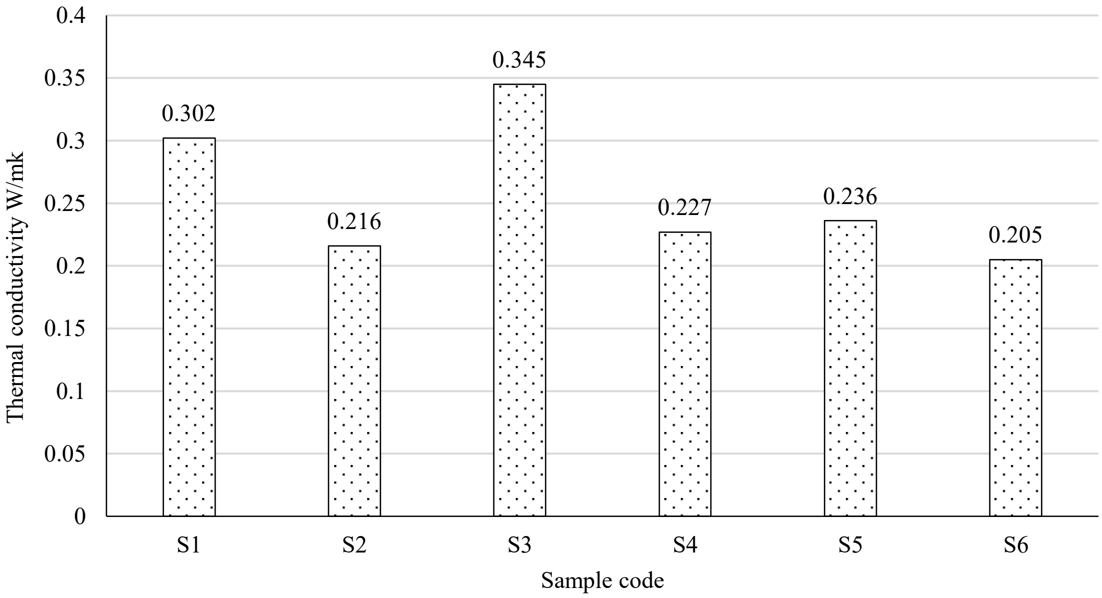


Figure 2. Thermal conductance.

The analysis observed that composite material, wherein Pineapple had been used as outer layers (designated as S2, S4, and S6), evidenced the coefficients of thermal expansion 0.1, 1, and 0.2×10−6/°C, respectively. The transmission of heat occurred in a smooth manner because reinforcements had been intercrossed in pattern [23]. The epoxy resin, which is used as the matrix material, increased the heat transfer considerably, thus enhancing the coefficient of linear thermal expansion (CLTE). Pineapple and epoxy resin were found to exhibit a wonderful binding property that created an improvement in heat transfer. The matrix component, evenly spread across the layers of pineapple fibre, enables the CLTE to increase in sample code "S2","S5" and "S6" regions.

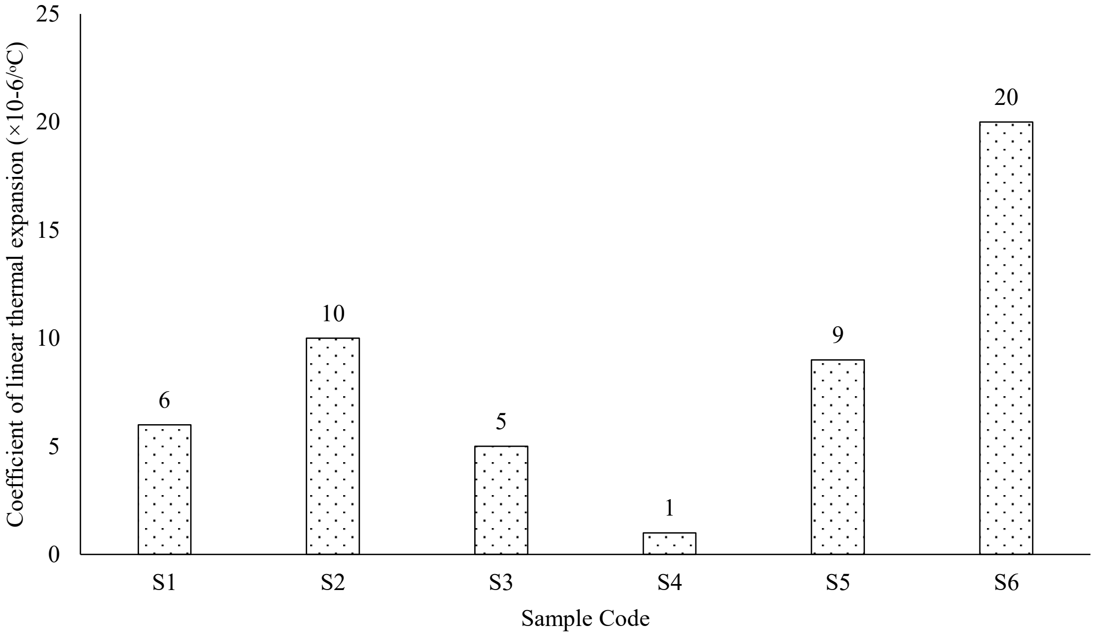


Figure 3. Coefficient of linear thermal expansion.

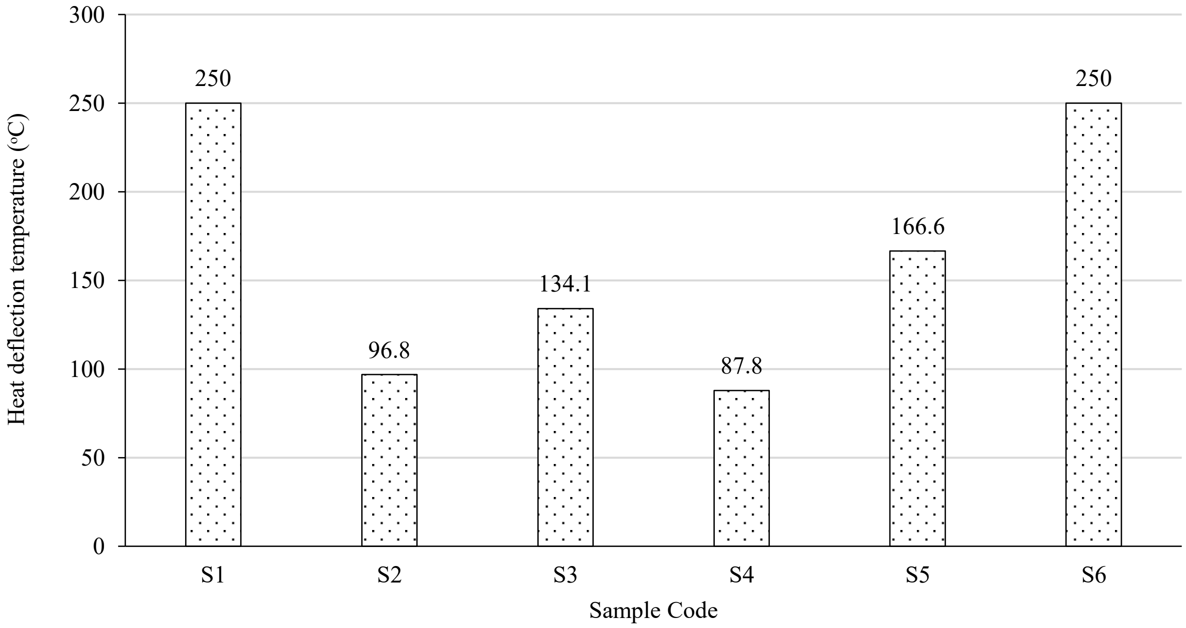
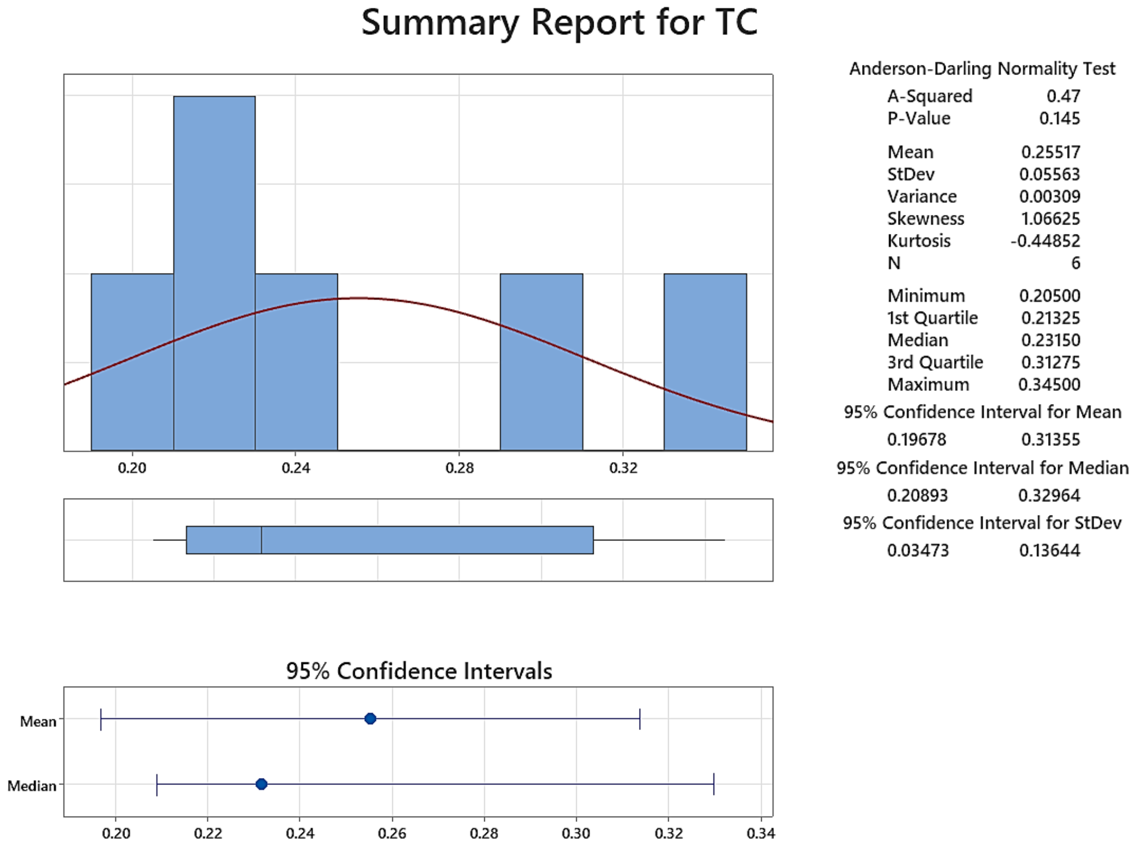


Figure 4. Heat deflection temperature.

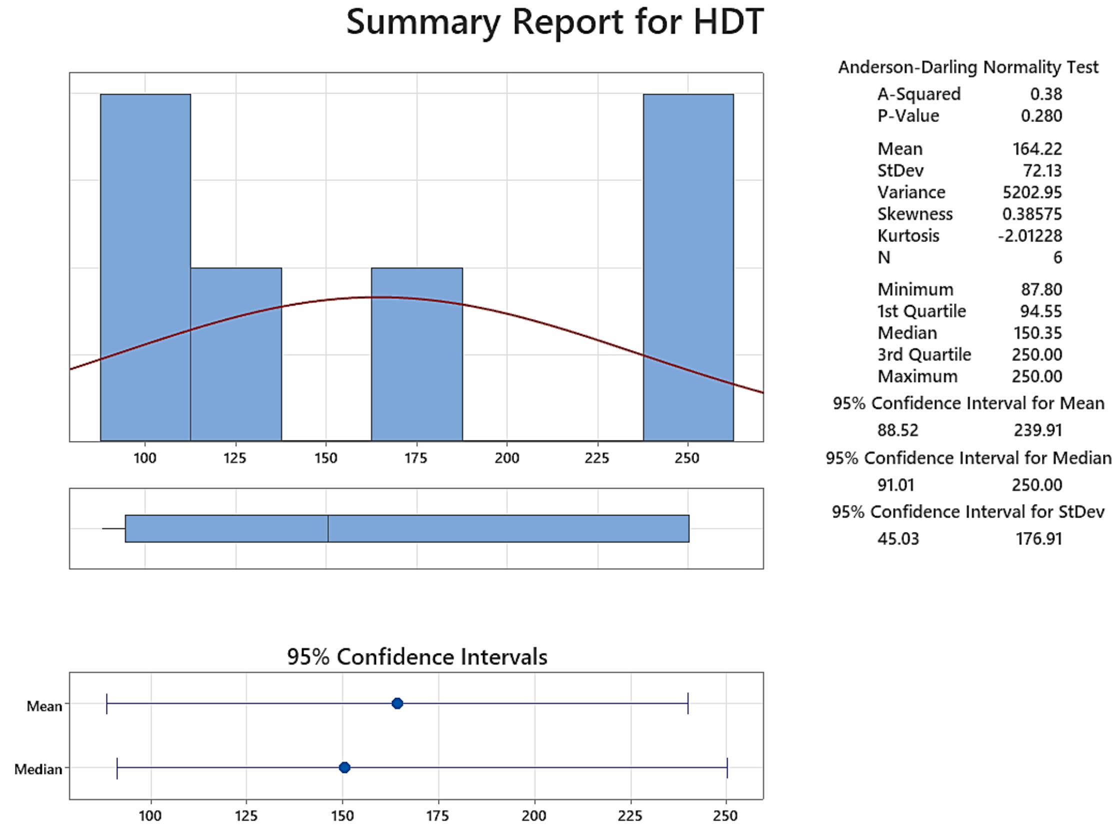


Summary Report for TC

```
Anderson-Darling Normality Test
    A-Squared            0.47
    P-Value             0.145

    Mean              0.25517
    StDev             0.05563
    Variance          0.00309
    Skewness          1.06625
    Kurtosis         -0.44852
    N                       6

    Minimum           0.20500
    1st Quartile      0.21325
    Median            0.23150
    3rd Quartile      0.31275
    Maximum           0.34500
95% Confidence Interval for Mean
    0.19678           0.31355
95% Confidence Interval for Median
    0.20893           0.32964
95% Confidence Interval for StDev
    0.03473           0.13644
```



Summary Report for HDT

```
Anderson-Darling Normality Test
    A-Squared            0.38
    P-Value             0.280

    Mean               164.22
    StDev               72.13
    Variance          5202.95
    Skewness          0.38575
    Kurtosis         -2.01228
    N                       6

    Minimum             87.80
    1st Quartile        94.55
    Median             150.35
    3rd Quartile       250.00
    Maximum            250.00
95% Confidence Interval for Mean
    88.52              239.91
95% Confidence Interval for Median
    91.01              250.00
95% Confidence Interval for StDev
    45.03              176.91
```

Figure 5. Statistical analysis of thermal conductivity (TC) and Heat Deflection Temperature (HDT) is displayed in the graph.

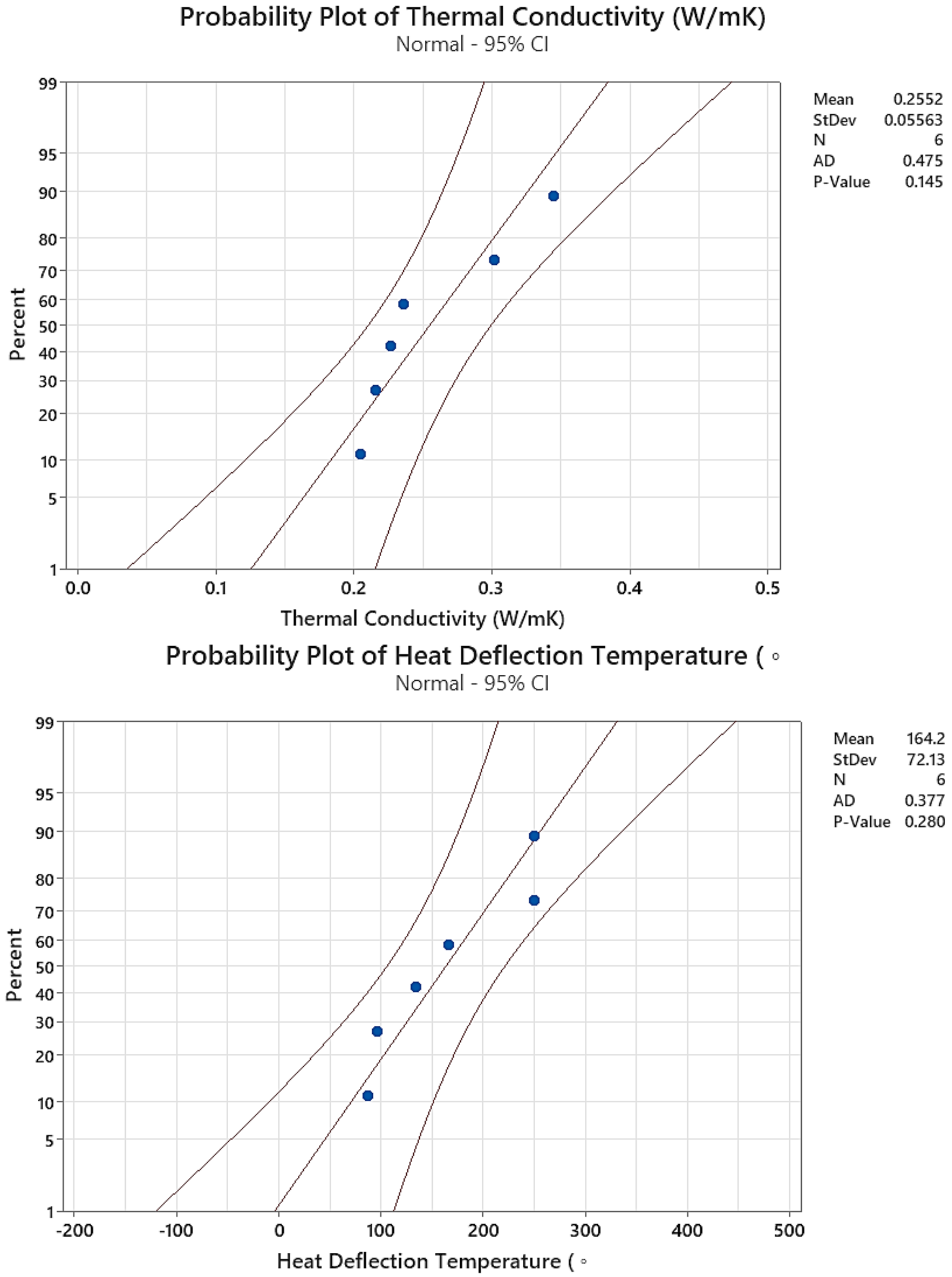


Figure 6. Statistical analysis of thermal conductivity (TC) and Heat Deflection Temperature (HDT) is displayed in the graph.

Heat deflection temperature

The heat deflection temperature acquired from the different varying stacking sequences is shown in Figure 4. This heat deflection test can be used to determine the short-term heat resistance [24]. It was noticed that each hybrid bio composite's Heat deflection temperature of differed depending on the stacking order. The hybrid composite designated as 'S1 & S6' demonstrated the maximum heat deflection temperature (HDT) of 250 °C kg^{-1}. The reinforcement fibers' alternating layers functioned as insulating layers, enabling the matrix materials to withstand higher temperatures compared to other stacking sequences. Hybrid composite 'S1 & S6' which can withstand high temperatures is suitable for insulation applications.

Pineapple fibers are perfect for high-temperature applications because of their increased thermal conductivity, higher heat deflection temperature, and improved structural integrity under heat and Ramie fibers are more suitable for moderately heated conditions where insulation is a top concern due to their lower strength and lower heat deflection temperature, but they also provide superior thermal insulation with lesser thermal conductivity. The stacking sequence (arrangement of P and R layers) strongly affects composite performance. Pineapple-rich or balanced hybrid stacks (e.g., S1, S3, S5) show higher thermal stability, while ramie-rich stacks (e.g., S2, S4) provide better insulation but lower thermal tolerance.

The Table 3. Shows experimental results of Hybrid composite in Different stacking sequence .The statistical analysis of response thermal conductivity and Heat Deflection Temperature values obtained with the Minitab 22 software presented above is shown in Figure 5. and 6. The experimental value of thermal conductivity (TC) and Heat Deflection Temperature (HDT) is found to have a probability of 0.145 and 0.287 since p-values are larger than 0.05, indicating that the data is accepted and that the value is normally distributed. Figure 6 shows comparable p-values at 95% of the significance threshold. The lowest and greatest values thermal conductivity (W/mK) are found to be 0.205 and 0.435, respectively, similarly the Heat Deflection Temperature was found 87.86◦C and 250◦C.

Table 3. Hybrid composite experimental results.

Specimen Code	stacking sequence	Thermal Conductivity (W/mK)	Heat deflection temperature (◦C)	Coefficient of linear thermal expansion (/◦C)
S1	PPRRRPP	0.302	250	6x10^{-6}
S2	RRPPPRR	0.216	96.8	1x10^{-5}
S3	PRRPRRP	0.345	134.1	5x10^{-6}
S4	RPPRPPR	0.227	87.8	1x10^{-6}
S5	PRPRPRP	0.236	166.6	9x10^{-6}
S6	RPRPRPR	0.205	250	2x10^{-5}

CONCLUSIONS

In conclusion, of stacking sequence of eco-friendly Pineapple / ramie composites was plays a critical role in determining their thermal behavior. Parallel ply orientations result in enhanced thermal stability and heat absorption, making them favorable for applications requiring efficient heat management. The sample's thermal examination led to the following findings:

- The maximum measured thermal conductivity was achieved by the sample S3 at 0.345 W/mK. The minimum conductivity was measured by 0.205 W/mK sample S6.
- Low thermal expansion coefficient achieved in sample S. In contrast, sample S6 showed a high expansion coefficient, likely due to weaker interfacial adhesion and higher anisotropy in fiber orientation. Ramie fibers at the sample edges demonstrated superior resistance to thermal expansion, indicating strong intermolecular forces and reduced structural distortion under
- The thermal deflection temperature (HDT), an important parameter that determines a material's resistance to softening under load, was the highest in sample S1 (250 °C) and the lowest in sample S4 (87.5 °C). This results determine that a hybrid stacking sequence had with ramie fibers as the Skin layers and pineapple fibers in the core produces a thermally stable composite with improved thermal resistance. The strong interfacial adhesion between the resin and fibers in these configurations contributes to increased stiffness, reducing the impact of thermal stress and deformation.

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