

Article

Recycled PET Sandwich Cores, Waste-Derived Carbon Additive, and Cure-Rate Control: FTIR/SEM Study of Flexural Performance in Flax Fiber-Reinforced Composites

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Abstract

To address circularity and resource recovery in modern structural applications, industry is seeking materials that are sustainable and lightweight. Although natural fiber-reinforced composites offer sustainability advantages, their mechanical properties remain inferior to those of synthetic fiber systems, limiting practical deployment. Flax fibers were selected as reinforcement due to their high specific stiffness, biodegradability, and wide availability. This study implements a three-level strategy to enhance the flexural performance of flax fiber-reinforced composites: at the process level, curing under distinct heating rates to promote a more uniform polymer network; at the material level, incorporation of a carbonaceous additive derived from fuel-oil furnace waste to strengthen interfacial adhesion; and at the structural level, adoption of a sandwich configuration with a recycled PET core to increase section bending inertia. Specimens were fabricated via vacuum-assisted resin transfer molding (VARTM) and tested using a three-point bending method. Mechanical testing shows clear improvements in flexural performance, with the sandwich architecture yielding the highest values and increasing flexural strength by up to $4.52\times$ relative to the other conditions. For the curing series, FTIR indicates greater reaction extent, evidenced by lower intensities of the epoxide ring at 915 cm^{-1} and glycidyl/oxirane band near 972 cm^{-1} , together with a more pronounced C–O–C stretching region, consistent with the higher flexural response. While SEM observations revealed interfacial debonding at 5% FCB, a hybrid mechanism with crack deflection appeared at 10%. This transition created tortuous crack paths, consistent with the higher flexural strength and modulus at 10% FCB. A distinctive feature of this work is the integration of three reinforcement strategies—controlled curing, waste-derived carbon additive, and recycled PET sandwich design. This integration not only enhances the performance of natural fiber composites but also emphasizes sustainability by valorizing recycled and waste-derived resources, thereby supporting the development of greener composite materials.

Keywords: natural fiber; sandwich composite; FTIR spectroscopy; SEM



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1. Introduction

The global transition toward the adoption of sustainable and environmentally friendly materials has spurred growing interest in natural fiber-reinforced polymer composites (NFRPCs) for structural and semi-structural applications [1,2]. Among various natural

fibers, flax stands out as a particularly promising candidate due to its high specific stiffness, biodegradability, affordability, and broad availability [3–5]. Extracted from the bast tissues of *Linum usitatissimum*, flax fibers possess favorable tensile properties, rendering them suitable for reinforcement in both thermoset and thermoplastic matrices [6–8]. Flax-based composites have been widely utilized in applications such as automotive interior panels, furniture, sports equipment, and construction components, especially in cases where lightweight performance and environmental compatibility are key considerations [9–12].

Polymer-matrix composites, while offering substantial weight reduction and high specific mechanical properties, are not without inherent drawbacks that limit their broader application. From an environmental standpoint, most thermosetting resins, including epoxy, are synthesized from petroleum-based feedstocks and are difficult to recycle due to their irreversible crosslinked structure. This lack of recyclability contributes to long-term waste accumulation and environmental persistence once the composites reach end-of-life [13–15]. In addition, disposal through incineration can release hazardous by-products, further exacerbating ecological concerns. Addressing these sustainability challenges is crucial as industries move toward a circular economy. From a performance perspective, polymer matrices also exhibit thermal limitations. Above their glass transition temperature (T_g), epoxy and other thermoset systems undergo softening and a rapid decline in stiffness, strength, and dimensional stability, thereby restricting their load-bearing capacity under high-temperature service conditions [16,17]. Prolonged exposure to elevated temperatures can also accelerate microcracking, oxidative degradation, and interfacial debonding between the fiber and matrix. These factors highlight the necessity of adopting improved processing strategies and hybrid designs that can mitigate both environmental and thermal shortcomings, ensuring that natural fiber-reinforced composites remain viable in demanding structural applications.

In addition to these matrix-related concerns, flax fiber-reinforced composites still suffer from limitations in mechanical performance, particularly in terms of flexural strength. A major issue lies in the poor interfacial adhesion between the hydrophilic flax fibers and hydrophobic matrices such as epoxy resin, which results in fiber pull-out, interfacial debonding, and inefficient stress transfer [18–22]. Moreover, thermoset matrices are inherently brittle, leading to rapid and catastrophic crack propagation, thereby compromising the toughness and ductility of the composite as a whole [23–27]. These challenges hinder the structural use of flax/epoxy systems and necessitate the development of improved materials and processing strategies.

Recent studies have proposed various strategies to address these issues. One effective approach involves optimizing the epoxy curing conditions, particularly through the use of a low heating rate during curing. Gradual temperature increases promote uniform thermal distribution, reduce thermal gradients, and minimize internal stresses that often lead to microcracks and fiber debonding [28–31]. Controlled curing also enhances polymer cross-linking, resulting in a matrix with superior mechanical strength and improved interfacial bonding with the fibers. Under the epoxy curing conditions investigated, FTIR spectroscopy was employed to provide clearer mechanistic insight by analyzing absorption bands. Signals of reactive groups were quantified relative to an internal reference band to directly track polymer network formation [32–35]. Accordingly, FTIR is well suited to assess the effects of temperature, curing time, heating rate, and resin-to-hardener stoichiometry on the degree of conversion and network homogeneity.

Another widely adopted strategy is to enhance the toughness of the matrix by incorporating additives such as reactive elastomers, thermoplastic particles, or bio-based plasticizers [36–38]. These additives act as energy absorbers during deformation, increasing fracture toughness, blunting crack tips, and slowing down crack propagation [39,40]. In

the case of flax fiber-reinforced composites, bio-based additives are particularly attractive as they align with the environmental objectives of natural fiber-reinforced systems [41–43].

Beyond matrix modification and resin curing optimization, the incorporation of a sandwich structural design has been shown to significantly enhance the flexural stiffness and resistance to bending deformation. The use of lightweight core materials such as polymer foams or honeycombs increases the moment of inertia without substantially adding to the overall weight of the structure [44–46]. Sandwich composites comprising natural fiber skins and polymer foam cores have demonstrated practical potential in applications such as automotive flooring and building panels. However, studies integrating this approach with toughness enhancement and optimized curing techniques remain limited.

While each of the aforementioned strategies—low heating rate curing, toughening additive incorporation, and sandwich structural design—has shown promising individual effects, their combined influence on flexural properties has been largely understudied. Prior research typically focuses on isolated parameters without fully considering synergistic effects, process compatibility, or holistic structural performance. For instance, Tran et al. [47] focused primarily on curing cycle optimization, while Ouyang et al. [40] emphasized matrix toughening via additive incorporation. Therefore, the integration of these techniques in a scalable and cost-effective manner remains a critical research gap.

Accordingly, this study investigates the individual and combined effects of three strategies on the flexural behavior of flax fiber-reinforced composites: low heating-rate curing, matrix strengthening using an industrial waste-derived additive, and a sandwich architecture employing a recycled PET core. Specimens were fabricated using vacuum-assisted resin transfer molding (VARTM) with tightly controlled curing schedules, followed by three-point bending tests to evaluate flexural strength. FTIR spectroscopy was used to elucidate polymer network formation, and scanning electron microscopy (SEM) was employed to analyze fracture surface morphology and the dominant damage mechanisms.

The results provide novel insights into the relationships between processing strategies and mechanical performance in natural fiber composites. Furthermore, the findings highlight practical routes for enhancing the structural capability of bio-based composites, supporting the broader adoption of flax fiber-reinforced systems in engineering applications where both high flexural performance and lightweight design are critical.

2. Methodology

In this study, the flax fiber-reinforced composites were investigated through three separate processing approaches to evaluate the effects of each enhancement strategy on the flexural mechanical properties. The investigated strategies include (1) controlling the curing conditions of the epoxy matrix, (2) incorporating additives, and (3) implementing a sandwich structural design. Each process was independently assessed to isolate its contribution to mechanical performance under bending loads. The results from these individual evaluations were then collectively analyzed to provide a comprehensive understanding of their combined effects and to identify the most effective approach for improving the overall flexural performance of the composite system.

2.1. Materials and Fabrications

The primary reinforcement material used in the composites was unidirectional flax fiber with an areal weight of 200 g/m², procured from Easy Composites Ltd. (Stoke-on-Trent, UK), as illustrated in Figure 1a. The fibers exhibit diameters ranging from 14.78 to 28.52 µm, as observed in Figure 1b, highlighting their suitability for load-bearing applications in the composite structure. Prior to composite fabrication, the fibers were dried at 60 °C for 1 h and subsequently stored in vacuum-sealed bags at room temperature.

for 24 h to minimize moisture uptake. This pre-treatment ensured stable fiber conditions during processing. The matrix system consisted of ER570 epoxy resin combined with a hardener, purchased from BRP Carbon (Bangkok, Thailand), which is well-suited for the vacuum-assisted resin transfer molding (VARTM) process (Figure 2). The selection of the vacuum infusion technique offers several advantages in composite fabrication: it ensures good impregnation between the reinforcing fibers and the matrix, promotes a uniform fiber-to-resin ratio, and minimizes the presence of voids and internal discontinuities in the final composite product. This is achieved through the continuous application of atmospheric pressure on the laminate throughout the entire molding process.

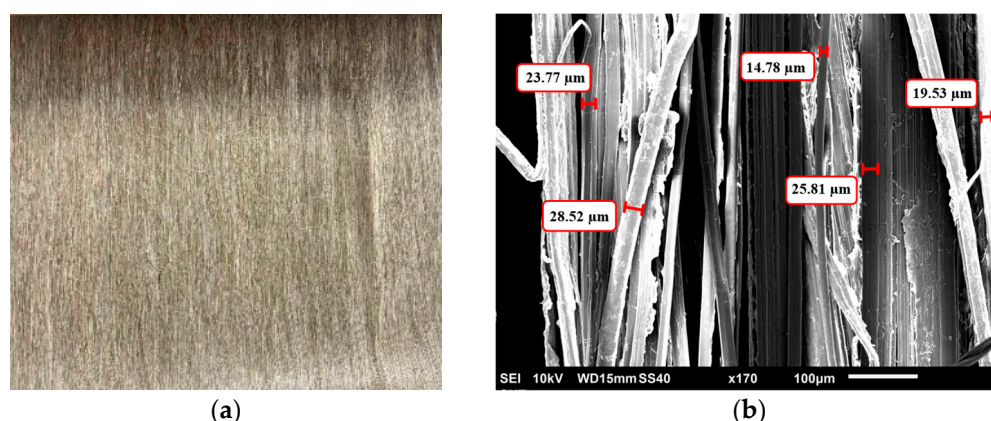


Figure 1. Flax fibers: (a) woven alignment in macroscopic view and (b) individual fiber diameters observed by means of SEM.

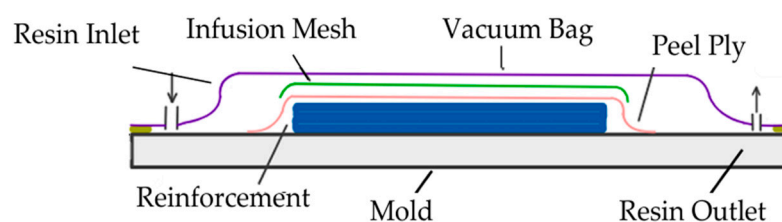


Figure 2. Vacuum-Assisted Resin Transfer Molding (VARTM).

2.2. Experimental Groups

2.2.1. Experimental Group 1: Matrix Curing Rate Control

This experimental group focuses on evaluating the influence of the resin curing temperature ramp rate on the mechanical properties of the composite. The primary objective is to regulate the crosslinking reaction within the epoxy matrix in a manner that enhances interfacial bonding with the flax fibers. Composite samples were prepared specifically to assess how the curing rate affects fiber–matrix adhesion and stress distribution within the system.

According to the manufacturer’s technical datasheet, the ER570 epoxy resin system is typically processed by initially curing at room temperature until the laminate has sufficiently hardened and can be demolded. A staged post-curing process is then applied, using a slow heating rate (1 °C/min) with intermediate holding steps at multiple temperatures (e.g., 50–70–90 °C). This recommended cycle is intended to achieve a higher degree of cure, reduce residual stress, and thereby improve the flexural performance of the laminate.

In contrast to this standard procedure, the experimental approach in the present study deliberately employed two simplified curing conditions, fast and slow profiles, representing two extreme cases that deviate from the standard. This design was selected to highlight the effect of heating rate and isothermal holding on composite properties:

- **Fast Curing Condition:** The composite was cured by applying a rapid heating rate of 5 °C/min from room temperature to 100 °C, which is the temperature at which the epoxy system achieves complete crosslinking. This temperature was maintained for 3 h, as illustrated in Figure 3. The purpose of this curing condition was to accelerate the polymerization process and promote the development of a fully crosslinked polymer network. Specimens prepared under this condition served as the baseline for comparison with the slow curing condition.
- **Slow Curing Condition:** In this condition, the composite was subjected to a slower heating rate of 1 °C/min starting from room temperature up to 60 °C. The temperature was held at this point for 1 h to lower the resin viscosity, thereby facilitating more uniform wetting and distribution throughout the fiber architecture. After the hold, the temperature was increased at the same rate to reach 100 °C and held for 3 h to complete the curing process, as shown in Figure 4.

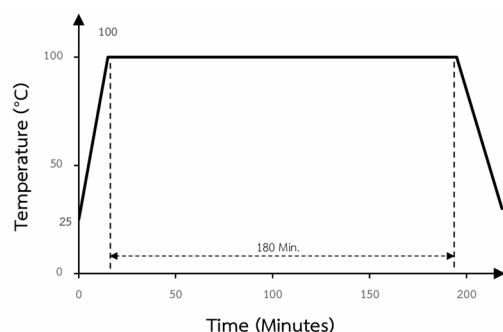


Figure 3. Resin curing profile at a heating rate of 5 °C/min.

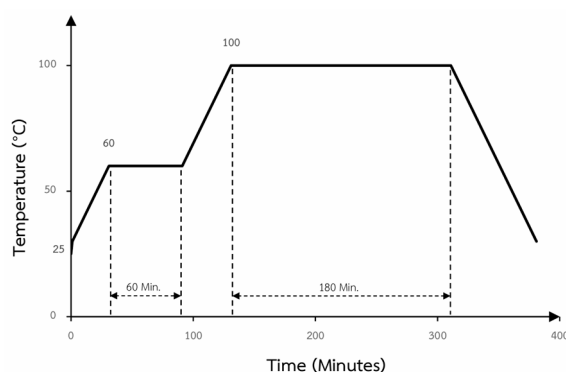


Figure 4. Resin curing profile at a heating rate of 1 °C/min.

After curing, both sets of composite samples were stored in vacuum-sealed bags at ambient room temperature for 24 h under controlled humidity conditions ($\pm 2\%$ RH) to prevent moisture-related variability in properties. The specimens were then trimmed to dimensions in accordance with ASTM D790 [48] standard specifications for subsequent three-point bending tests.

2.2.2. Experimental Group 2: Incorporation of Additives

In this experimental group, additive materials were incorporated into the composite fabrication process to investigate the effect of additive content on the mechanical properties of flax fiber-reinforced composites. The additive used in this study was derived from carbon-rich soot collected from furnace oil combustion chambers and supplied by Tipco Asphalt Public Company Limited (Bangkok, Thailand). The raw soot was sieved and purified to remove impurities, leaving behind fine carbon powder suitable for composite applications, as shown in Figure 5a. The EDS analysis of the soot (Figure 5b) revealed

that carbon is the predominant element, with a substantially higher content than other detected elements, thereby confirming its classification as carbon-rich soot. In addition, SEM observations (Figure 6) showed that the particle size of the soot additives ranged approximately from 5.94 to 25.57 μm . The carbon-based additive was blended into the epoxy resin at three different concentrations: 5%, 10%, and 15% by weight. Mixing was performed using a magnetic stirrer at a speed of 600 revolutions per minute for 15 min, which was sufficient to ensure uniform dispersion of the additive within the resin matrix. Following mixing, the resin was combined with an appropriate amount of hardener, and the mixture was subjected to degassing to remove entrapped air introduced during the stirring process. After degassing, the modified resin was used in the vacuum infusion process for composite fabrication. Upon completion of curing and conditioning at room temperature, the composite laminates were trimmed to standard test dimensions in accordance with ASTM D790, as performed with the specimens in Experimental Group 1.

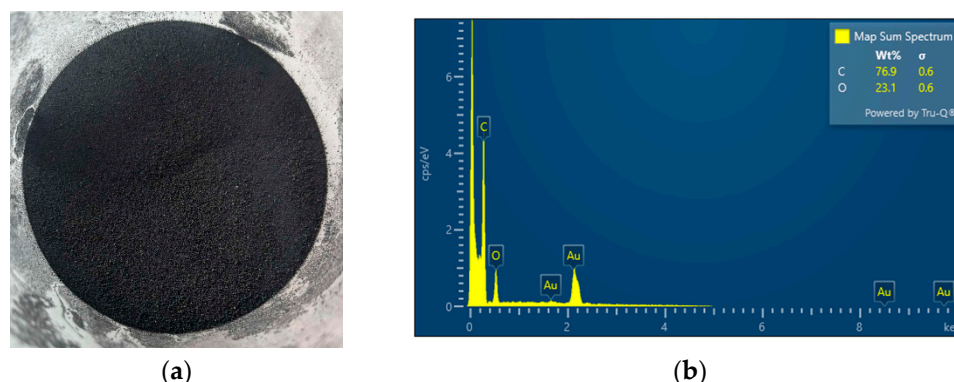


Figure 5. Carbon-rich soot from furnace oil combustion: (a) macroscopic powder appearance; (b) EDS spectrum.

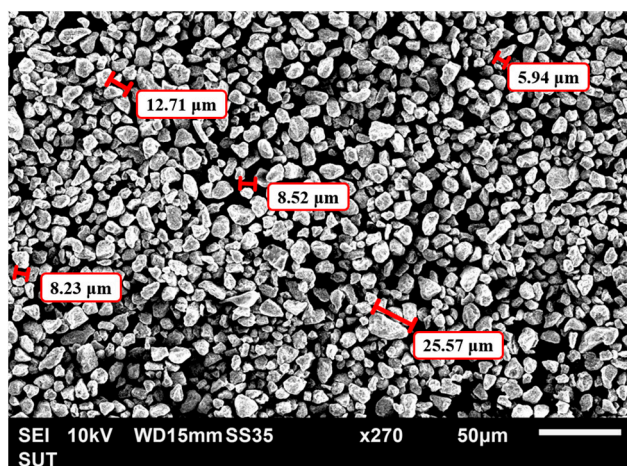


Figure 6. SEM image of the carbon-based additive (5.94–25.57 μm).

2.2.3. Experimental Group 3: Sandwich Composite

This experimental group aims to enhance the flexural resistance of the composite through the incorporation of a sandwich structure, which involves embedding a lightweight core material between the composite skins. The selected core for this study is Lantor Soric XF, a honeycomb-like core manufactured from recycled PET plastic waste and purchased from BRP Carbon (Bangkok, Thailand), aligning with the study's objective of promoting sustainability in composite design, and used in flat sheet form with thicknesses of 3–12 mm as summarized in Table 1. Its honeycomb-like internal morphology not only minimizes weight but also provides resin flow channels that are highly suitable for vacuum infusion,

thereby facilitating impregnation while maintaining structural efficiency. The sandwich structure was assembled by placing the core together with the flax fiber reinforcement layers in a single lay-up sequence. The entire assembly was then fabricated using the vacuum infusion process, as shown in Figure 7. This method ensures strong adhesion between the core and the fiber-reinforced skins, while also allowing the resin to flow uniformly and infiltrate both the flax fibers and the surface of the core, minimizing the risk of delamination or dry spots. After the molding process was completed, the laminates were trimmed to meet the dimensional requirements of ASTM C393 [49], the standard used for evaluating the flexural performance of sandwich composite structures.

Table 1. Specimen identification and testing parameters.

Experiment Group	Condition	Name	Width (mm)	Thickness (mm)
Resin Curing Control	Heat rate			
	5 °C/min	HR5	16.1 ± 0.2	1.7 ± 0.2
	1 °C/min	HR1	15.9 ± 0.2	1.5 ± 0.2
FCB Addition	% Additive			
	0%	FCB0	15.02 ± 0.2	4.52 ± 0.2
	5%	FCB5		5.23 ± 0.2
	10%	FCB10		6.21 ± 0.2
	15%	FCB15		6.98 ± 0.2
Sandwich Structure	Core Thickness			
	3 mm	C3	15.02 ± 0.2	5.02 ± 0.2
	6 mm	C6		7.72 ± 0.2
	9 mm	C9		10.33 ± 0.2
	12 mm	C12		12.21 ± 0.2

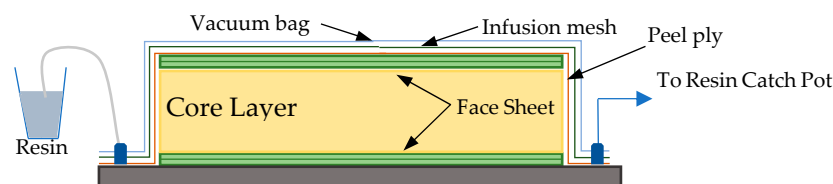


Figure 7. Sandwich Structure Manufacturing.

2.3. Test Configuration and Specimen Identification

Composite specimens were assigned specific labels corresponding to their experimental groups, as summarized in Table 1. Each group consisted of five replicates, tested in accordance with ASTM standards. The use of five specimens per condition follows the requirements of the testing standards, ensuring sufficient data reliability. The stress and strain values for each sample were calculated using the equations provided in ASTM D790 (for resin control and additive groups) and ASTM C393M (for sandwich structures). Representative specimens prior to testing are shown in Figure 8, illustrating their geometry and dimensions. Results are reported as mean values, and error bars in the figures represent one standard deviation (SD) from the mean, based on $n = 5$ specimens for each group.

All composite tests were conducted on a universal testing machine (UTM; LLOYD LD100, 100 kN capacity, Copenhagen, Denmark) to determine the mechanical properties of each specimen set. The fracture regions were then examined using scanning electron microscopy (SEM; JEOL JSM-6010LV, Tokyo, Japan) to analyze microstructural features and damage mechanisms. In parallel, Fourier transform infrared spectroscopy (FTIR; Bruker TENSOR 27 with HYPERION 2000 microscope, Ettlingen, Germany) was employed as a non-destructive technique to monitor the curing behavior of the epoxy matrix and to

estimate the degree of conversion under low heating-rate profiles, by normalizing the intensities of reactive bands to an internal reference band.

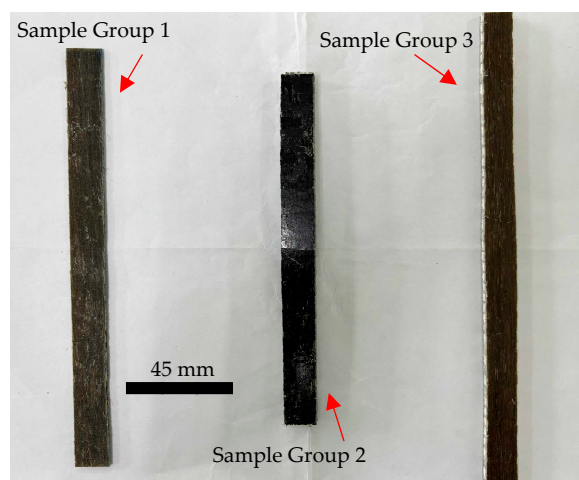


Figure 8. Representative composite specimens from the three experimental groups prior to mechanical testing.

3. Experimental Result and Analysis

This section focuses on the comparison and analysis of the mechanical properties of flax fiber-reinforced composites that were enhanced using three different strategies. The evaluation is primarily based on three-point bending tests to assess flexural performance. In addition, scanning electron microscopy (SEM) was employed to examine the internal structure of the fractured specimens, enabling detailed analysis of the failure mechanisms associated with each processing approach. This integrated methodology provides a comprehensive understanding of how each reinforcement strategy influences the flexural strength, flexural modulus, and deflection at fracture of the composite materials. Additional test results are provided in Supplementary Table S1. In each mixing proportion, five specimens were evaluated for consistency with a low median standard deviation ($SD/\bar{x} < 10\%$). Error bars were used to represent the variation in test results in the figures, reflecting the reliability and reproducibility of the results.

3.1. Effect of Resin Curing Control

In the experimental group investigating resin curing conditions, it was found that a gradual temperature ramp with a slow heating rate resulted in the highest average flexural strength of 144.192 N, as illustrated in Figure 9. This value was 1.13 times higher than that of the composite cured rapidly with a higher heating rate, which reached only 127.59 N, indicating that rapid thermal curing tends to reduce the flexural strength capacity of composites when compared to slower-curing systems. The load–deflection curves exhibited an initial linear region corresponding to elastic deformation, followed by a nonlinear region associated with matrix microcracking and progressive fiber/matrix debonding. Final failure was marked by an abrupt load drop, characteristic of brittle fracture in thermoset composites. The slower heating rate produced both higher load and greater deflection at failure, suggesting improved crosslinking and reduced internal stresses. Additionally, both the maximum flexural stress and modulus followed similar trends, increasing by 1.05 times and 1.32 times, respectively, as shown in Figure 10. The stress values were calculated in accordance with the relevant ASTM standards for flexural testing, while the modulus corresponds to the flexural modulus, determined from the slope of the initial linear portion of the stress–strain curve.

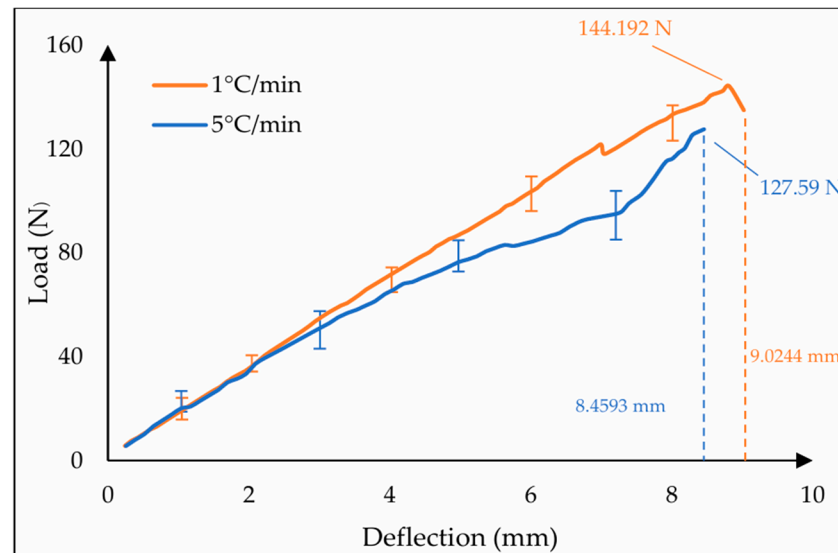


Figure 9. Load–deflection distribution (Experimental Group 1).

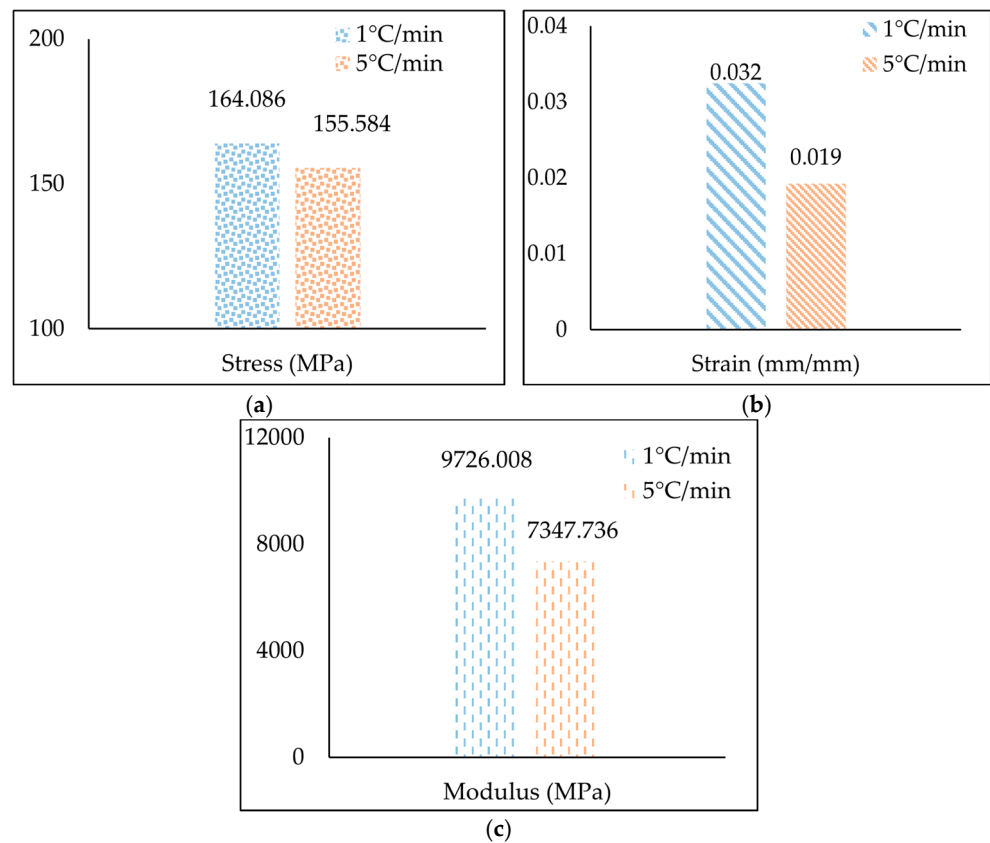


Figure 10. Specimen behavior in Experimental Group 1: (a) Stress, (b) Strain, and (c) Modulus.

The deflection behavior also indicated superior flexibility in the slow-curing condition, with the average maximum deflection reaching 9.0244 mm, which is 1.06 times greater than that observed in the rapidly cured composite (8.4593 mm). These results suggest that gradual crosslinking allows better molecular arrangement and more effective interfacial bonding between the resin and flax fibers, leading to improved load distribution and energy dissipation under bending.

When comparing the FTIR spectra (Figure 11) of the samples cured at 1 °C/min and 5 °C/min, the peak intensities at 915 cm^{-1} (assigned to the unreacted epoxy ring) and $\sim 972 \text{ cm}^{-1}$ (attributed to terminal glycidyl/oxirane groups) are markedly lower in the

1 °C/min sample than in the 5 °C/min sample, as confirmed by the intensity ratios A_{915}/A_{1600} and A_{972}/A_{1600} . This indicates that a greater extent of epoxy group consumption and ring-opening occurred under the slower curing rate of 1 °C/min. Simultaneously, the absorption band in the 1250–1050 cm^{-1} region, corresponding to C–O–C ether stretching, exhibits significantly higher intensity in the 1 °C/min sample, suggesting enhanced ether bond formation and a more tightly crosslinked polymer network. In contrast, the broader and more intense envelope at 3500–3200 cm^{-1} (O–H stretching) in the 5 °C/min sample reflects the presence of residual hydroxyl groups and/or greater heterogeneity in the curing process.

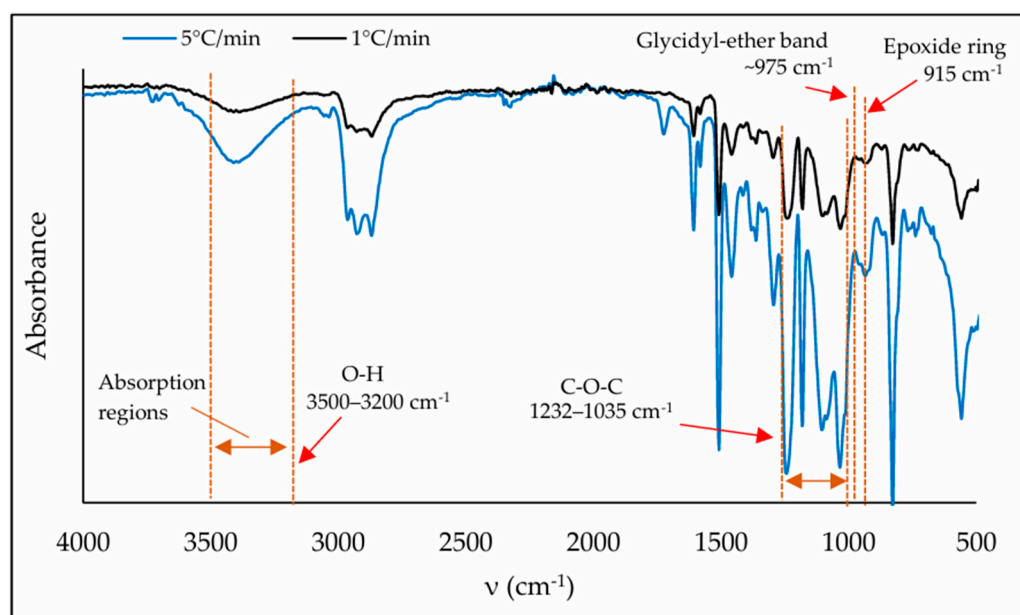


Figure 11. FTIR spectra of epoxy cured at 1 °C/min and 5 °C/min.

In contrast, the broad and more intense absorption envelope at 3500–3200 cm^{-1} (O–H stretching) observed in the 5 °C/min sample reflects a higher concentration of residual hydroxyl groups and/or greater heterogeneity in curing. Mechanistically, the reduction in the intensities of the 915 and ~972 cm^{-1} peaks in the 1 °C/min sample signifies that epoxy rings undergo more complete opening and consumption. During this process, hydroxyl groups (–OH) are generated, which further promote the formation of C–O–C ether linkages (as evidenced by the increased intensity in the 1250–1050 cm^{-1} region). Consequently, the crosslink density increases, resulting in a more continuous and tightly integrated resin network. Such a network structure enables more efficient stress transfer and improved resistance to deformation, thereby providing a straightforward explanation for why the 1 °C/min group exhibits higher flexural modulus, flexural strength, and greater deflection at failure compared with the 5 °C/min group.

3.2. Effect of FCB Additive Incorporation

For the experimental group involving the use of FCB (Furnace Combustion By-product) additives to enhance the strength of the composite, it was observed that all specimens containing FCB demonstrated a clear improvement in flexural load compared to the control samples without FCB additives, as illustrated in Figure 12a. Notably, the composite with 15% FCB exhibited the highest flexural load, reaching 418.698 N, which corresponds to an increase of 3.23 times relative to the non-reinforced baseline. These results indicate that the FCB additive contributes effectively to stress distribution and energy absorption under flexural loading.

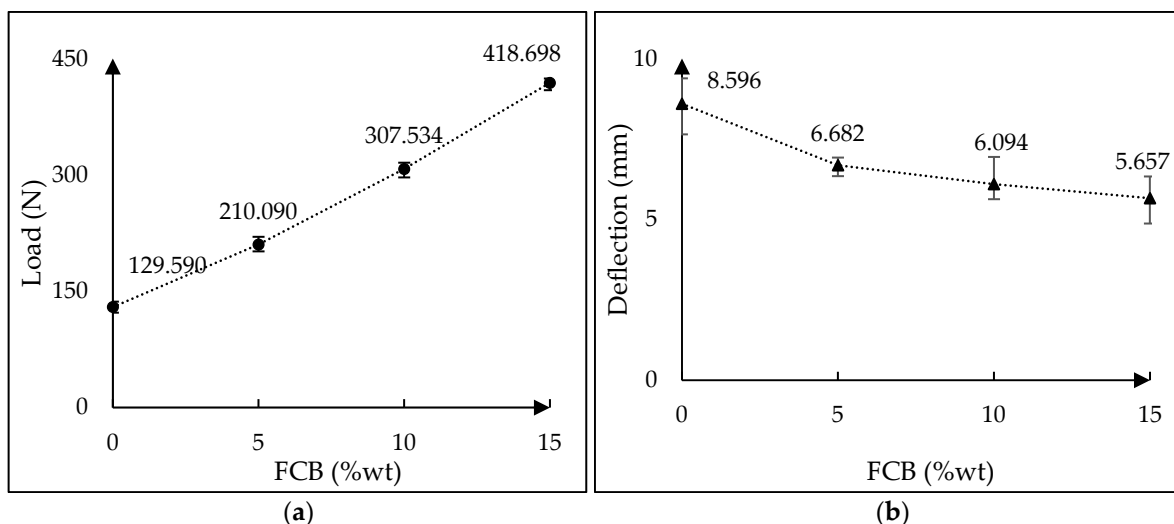


Figure 12. Effect of FCB content on flexural performance: (a) Maximum flexural load and (b) deflection at fracture.

In addition to load, deflection behavior was analyzed and is presented in Figure 12b. A consistent decrease in deflection was observed as the FCB content increased. The lowest deflection was recorded in the sample containing 15% FCB, with an average deflection at fracture of only 5.6569 mm. This suggests a shift in failure behavior toward a more brittle response with higher additive content. Therefore, an optimal range may lie between 5% and 10% FCB, balancing strength enhancement with acceptable ductility.

The corresponding flexural stress and strain values were also evaluated to provide a more comprehensive assessment of mechanical performance. Maximum flexural stress values are shown in Figure 13a, with the 15% FCB composite reaching 97.37 MPa. Strain values at fracture, presented in Figure 13b, reveal that increasing FCB content reduced ductility, with the 15% FCB composite showing a minimum strain of 0.022 mm/mm, confirming the trend toward a more brittle response.

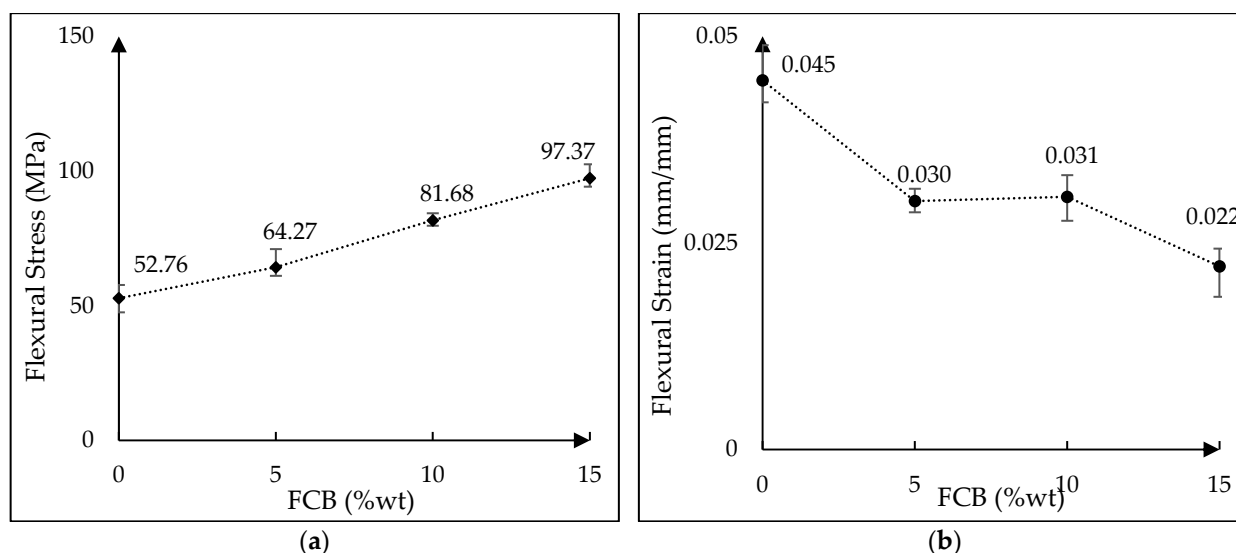


Figure 13. Effect of FCB content on flexural performance: (a) Maximum flexural stress and (b) flexural strain at fracture.

Flexural modulus values, derived from the slope of the initial linear region of the load–deflection curves, are presented in Figure 14. The modulus increased progressively with higher FCB content, with the 15% FCB composite reaching 4.361 GPa, indicating a

stiffer but less ductile behavior. This trade-off highlights the importance of optimizing additive concentration for specific structural applications.

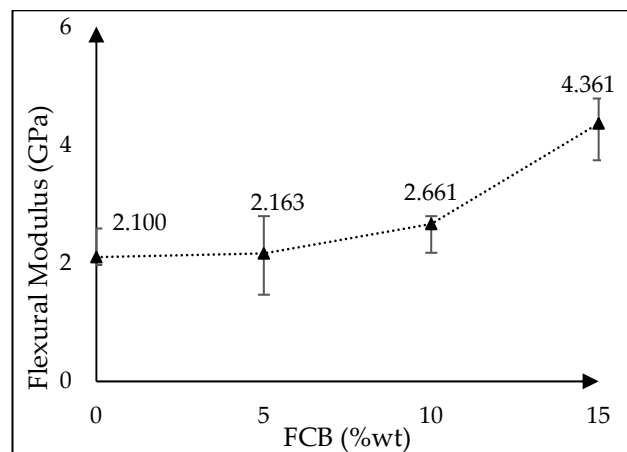


Figure 14. Effect of FCB content on flexural performance: Flexural modulus.

Furthermore, processing limitations were encountered during composite fabrication. It was found that exceeding 15% FCB content resulted in poor resin–additive mixing, as the viscosity increased beyond the capability of the magnetic stirrer to achieve uniform dispersion. This issue set the upper limit for additive concentration in this study, constraining the maximum FCB content to 15%.

SEM analysis demonstrates significant microstructural differences between composites containing 5% and 10% FCB additive. In Figure 15a (5% FCB additive), FCB particles are observed distributed along fiber surfaces, forming several small agglomerates. At the same time, interfacial gaps can be identified at fiber–matrix boundaries, indicating that fiber–matrix adhesion remains incomplete. The resulting crack path in this specimen tends to extend along the interface (interfacial debonding) rather than cutting across the fibers or the matrix, which indicates that the energy required for crack propagation is relatively low. The presence of interfacial gaps and straight crack paths suggests that stress transfer from the matrix to the fibers is limited, thereby restricting the overall mechanical performance of the composite at 5% additive loading. Although pronounced agglomeration is not yet observed, the ease with which cracks propagate along the interface is sufficient to constrain the strength of the material.

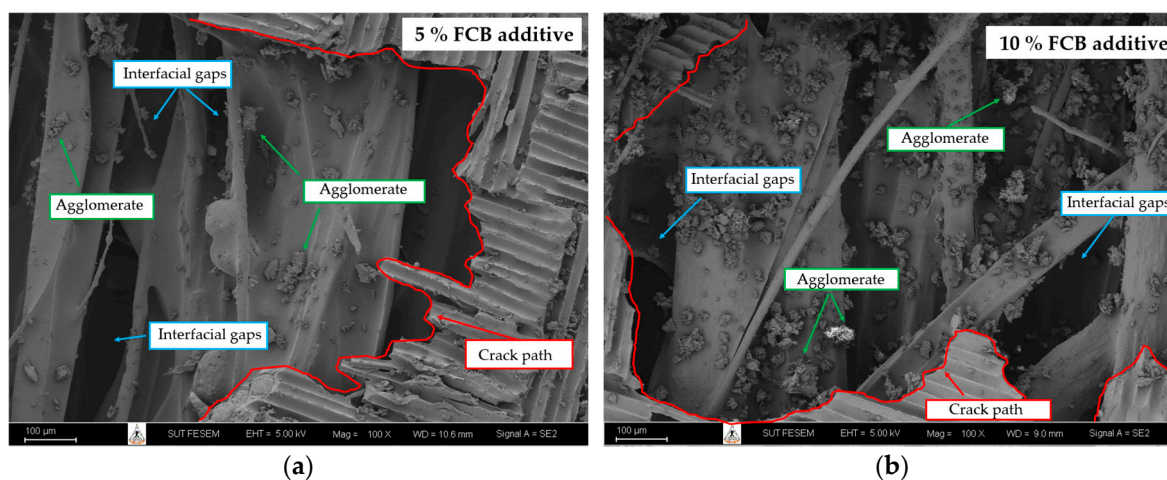


Figure 15. SEM overview of fracture mechanisms and additive dispersion: (a) 5% FCB and (b) 10% FCB.

In contrast, Figure 15b (10% FCB additive) demonstrates a pronounced microstructural transformation. Agglomerates appear larger and more densely distributed than in the 5% case, accompanied by more frequent interfacial gaps. However, the fracture morphology differs substantially, and the crack path is no longer straight and interface-dominated but rather curved and complex. This behavior is associated with crack deflection induced by FCB clusters and agglomerates. The crack is forced to navigate around these obstacles, which increases the fracture path length and raises the energy barrier for propagation. As a result, the composite with 10% FCB demonstrates enhanced toughness and higher flexural performance compared with the 5% system.

Although the presence of agglomerates and interfacial voids in Figure 15b constitutes microstructural defects that would typically impair mechanical properties, in this case the positive effects prevail. Enhanced mechanical interlocking between FCB particles and fibers, combined with crack deflection mechanisms, outweighs the negative influence of structural heterogeneity. In other words, although higher additive content introduces microstructural heterogeneities, these remain below the critical threshold at which material properties deteriorate. Instead, they contribute to greater energy absorption, resulting in a marked improvement in mechanical properties.

In summary, comparison of Figure 15a,b indicates a transition in the dominant failure mechanism. At 5%, failure is primarily governed by interfacial debonding alone, whereas at 10%, fracture proceeds via a hybrid mechanism combining interfacial debonding with crack deflection and crack around agglomerates. This transition demonstrates that higher additive content can be exploited to generate longer and more tortuous crack paths, thereby increasing fracture energy and overall strength. These observations are consistent with flexural testing results, which confirm that maximum flexural strength and modulus were achieved at 10% FCB additive.

3.3. Effect of Sandwich Structure Design

The incorporation of a sandwich structure with a lightweight core embedded between two composite skins significantly improved the flexural performance of the flax fiber-reinforced composites. This enhancement is primarily attributed to the increased overall thickness of the composite section, which leads to a higher moment of inertia and, consequently, greater resistance to bending loads. Among the tested samples, specimen C12 exhibited the highest average flexural strength, reaching 715.896 N, which represents an increase of 4.52 times compared to the composite without a core, as shown in Figure 16. On the other hand, when examining the deflection behavior under load, it was found that specimen C3 exhibited the greatest deflection, averaging 21.493 mm making it the most flexible among the tested configurations. These results demonstrate that sandwich construction not only improves stress distribution and load transfer but also reduces stress concentrations in the central region of the specimen due to the enhanced moment of inertia. However, increasing the core thickness also leads to more brittle structural behavior, indicated by reduced deflection capacity. Therefore, selecting the appropriate core thickness must involve a trade-off between mechanical performance and structural flexibility, especially in applications requiring lightweight design.

Fractographic analysis revealed distinct failure modes depending on core thickness. For samples with thin cores (3–6 mm), cracks primarily initiated in the face sheets and penetrated slightly into the core, indicating that failure was driven by the rupture of the fiber-reinforced layers under tension, as illustrated in Figure 17a,b. In contrast, samples with thicker cores (9 mm) exhibited failure dominated by shear stresses within the core itself. The face sheets remained largely intact, while the core developed extensive cracking from the bottom to the top surface, suggesting shear-induced failure, as shown in Figure 17c.

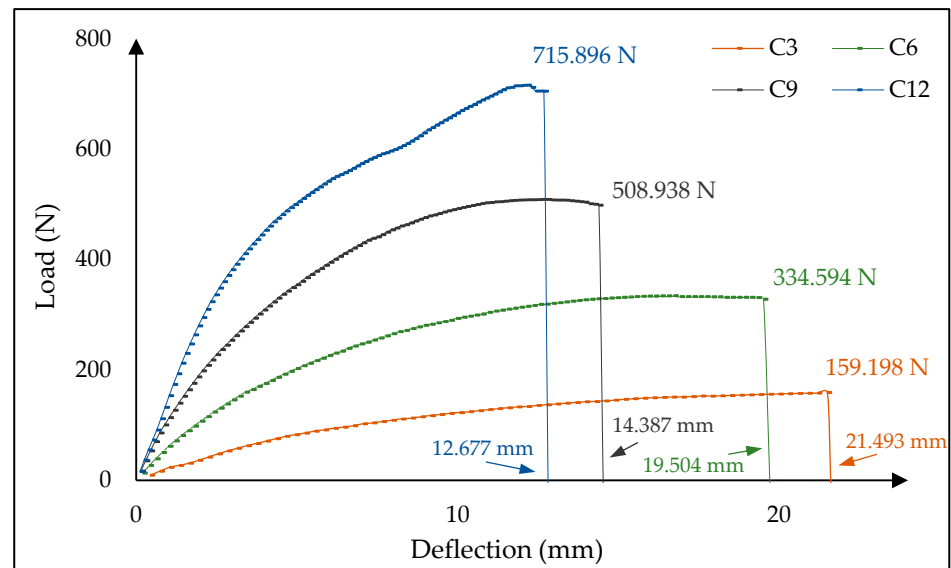


Figure 16. Load–deflection distribution in Experimental Group 3.

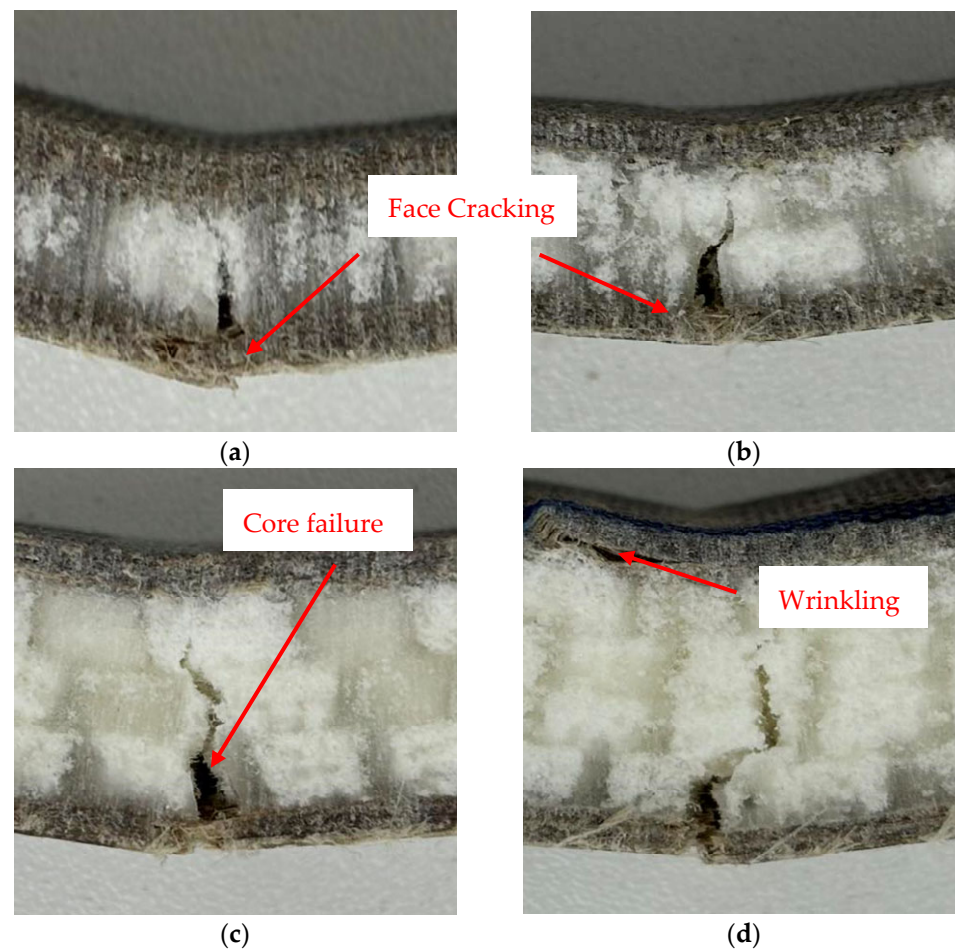


Figure 17. Failure Mode in the Specimen from Experimental Group 3: (a) Sample C3, (b) Sample C6, (c) Sample C9, and (d) Sample C12.

In the case of the thickest core (12 mm), the failure morphology included wrinkling of the bottom face sheet (face sheet wrinkle), as shown in Figure 17d, along with signs of local buckling in the top skin. This indicates that the excessive core-to-skin ratio led to stress localization that could not be effectively distributed, resulting in premature failure and a significant reduction in the composite's ability to deform. These findings suggest that a core

thickness of 3–6 mm is optimal for achieving a balance between load-bearing performance and structural flexibility, particularly for applications that do not involve extremely high mechanical demands.

3.4. Overall Improvement Outcomes

Among the three reinforcement strategies investigated for enhancing the performance of flax fiber-reinforced composites, it was found that gradual resin curing resulted in improved flexural bearing compared to rapid curing, with an increase of 1.13 times in flexural load. However, to further enhance the composite's flexural resistance, the other two approaches additive incorporation and sandwich structural design also yielded highly satisfactory results. The use of FCB additives led to a strength improvement of up to 3.23 times, while the sandwich composite configuration achieved the highest increase of 4.5 times compared to the baseline.

Nonetheless, as previously discussed, the degree of deflection is a critical factor to consider when selecting the optimal reinforcement strategy. Both high additive content and excessively thick cores contributed to increased brittleness, reducing the composite's ability to deform under load. Therefore, while each strategy offers unique advantages, the sandwich structural design stands out as the most effective approach overall, offering not only excellent flexural strength but also a promising balance between stiffness and toughness making it the most suitable solution for applications requiring both strength and resilience.

4. Conclusions and Suggestions

4.1. Conclusions

This study explored three complementary strategies for enhancing the flexural performance of flax fiber-reinforced epoxy composites: (i) tailoring the epoxy curing schedule under a low heating-rate profile, (ii) incorporating furnace combustion byproduct (FCB) additives, and (iii) implementing a sandwich laminate with a recycled PET core. Flexural properties were evaluated via three-point bending, while SEM and FTIR analyses provided insight into the microstructural and correlations with mechanical behavior.

Curing at a low heating rate of 1 °C/min delivered a flexural strength of 164.0859 MPa and a flexural modulus of 9.73 GPa, exceeding the fast-cured condition by 1.05 times, and produced a larger mid-span deflection of 9.0244 mm. The improved matrix continuity and enhanced fiber–matrix adhesion observed in FTIR results confirm that gradual heating reduces residual stresses and promotes more uniform crosslinking. These findings suggest that a low heating rate mitigates residual cure stresses, yields a more continuous matrix, and enhances fiber–matrix adhesion, collectively improving flexural performance. Importantly, the combined increase in flexural strength, modulus, and deflection demonstrates that the composites not only resist higher loads but also accommodate greater deformation before failure, pointing to a more favorable balance of stiffness and toughness. This improvement highlights the effectiveness of curing control as a practical processing strategy to overcome the inherent brittleness of thermoset matrices and to extend the suitability of flax/epoxy composites in demanding structural applications.

Incorporation of the FCB additive improved the flexural performance of the composites, increasing the maximum flexural load by 3.23 times. This trend is consistent with SEM evidence showing that at 5% FCB, fracture was dominated by interfacial debonding, whereas at 10%, a hybrid mechanism emerged, combining interfacial debonding with crack deflection and crack propagation around agglomerates. Such a transition promotes longer and more curve crack paths, thereby enhancing fracture energy and overall strength. These findings align with flexural test results, which confirmed that maximum flexural strength

and modulus were achieved at 10% FCB additive. The contrasting behavior at moderate versus high additive levels highlights the importance of optimizing filler concentration, as excess loading compromises toughness despite gains in stiffness. This finding underlines both the potential of waste-derived additives to strengthen natural fiber composites and the necessity of balancing reinforcement efficiency with damage tolerance for structural applications where energy absorption is critical.

The sandwich structure, particularly with a 12 mm thick Lantor Soric XF core, provided the highest flexural strength (715.896 N, or 4.52 times greater than the baseline). However, the 3 mm core yielded the greatest deflection (21.493 mm), demonstrating a favorable balance of strength and flexibility. The observed behavior can be explained by the increase in moment of inertia with thicker cores, which raises load-bearing capacity, while thinner cores retain higher compliance and energy absorption. The inherent flexibility and resin-flow channels of the recycled PET Soric XF core further contributed to both stiffness and deformation capacity. These results emphasize that core thickness is a key design parameter, enabling the tailoring of sandwich composites either for maximum strength or for improved toughness, depending on the demands of the intended structural application. Moreover, the use of recycled PET cores reinforces the sustainability aspect, offering both performance enhancement and environmental benefits.

Overall, the integration of the three strategies provides synergistic improvements that surpass individual effects—combining optimized curing, waste-derived reinforcement, and sustainable core materials into a coherent design approach. The outcomes present a practical guideline for tailoring natural-fiber composites toward specific stiffness–toughness requirements while aligning with sustainability goals. Nevertheless, the study was limited to flexural loading on small-scale specimens; future work should include full-scale structural testing and fatigue evaluation to validate the long-term performance of these green composite systems.

4.2. Toward Sustainable Composites

While natural fiber composites may not yet fully replace synthetic composites, the results of this study highlight the potential of flax fibers as reinforcement in structural applications, especially when processing techniques are optimized. The research also supports sustainability through the use of recycled materials: the FCB additive derived from furnace oil ash and the Lantor Soric XF core made from recycled PET. These findings suggest that natural fiber composites offer adequate performance for lightweight structural applications and can serve as eco-friendly alternatives to glass or carbon fiber in contexts such as green mobility, bio-based packaging, and energy-efficient building materials.

4.3. Application Recommendations

Based on the results, the following recommendations are proposed for selecting manufacturing strategies depending on specific application requirements:

For high strength and lightweight structural components (e.g., load-bearing wall panels and automotive covers), use slow curing combined with an optimized resin-to-fiber ratio.

For moderate reinforcement without increasing thickness (e.g., parts subjected to vibration or impact), incorporate 5–10% FCB, keeping in mind that excess additive may lead to brittleness.

For applications requiring high flexural resistance (e.g., flooring panels or load-distributing sheets), adopt a sandwich structure with a Lantor Soric XF core thickness of 3–6 mm, which offers an excellent balance of strength and flexibility.

4.4. Suggestions for Future Work

Increase the number of specimens in each group to enhance statistical reliability and potentially allow the use of parametric analysis.

Explore alternative reinforcement additives, such as graphene oxide or silica nanoparticles, which may offer superior performance compared to CTBN or nanoclay.

Include other mechanical tests such as tensile strength, shear strength, and impact resistance for a more comprehensive evaluation.

Investigate the environmental durability of the composites under varying conditions (e.g., high humidity and fluctuating temperatures) to validate their suitability for real-world applications.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/fib13100142/s1>, Table S1: Recycled PET Sandwich Cores, Waste-Derived Carbon Additive, and Cure-Rate Control: FTIR/SEM Study of Flexural Performance in Flax Fiber-Reinforced Composites (Data Output from Experimental).

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