EFFECT OF CELLULOSE NANOFIBERS FROM RED COCONUT PEDUNCLE WASTE AS REINFORCEMENT IN EPOXY COMPOSITE SHEETS

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Organic filler-reinforced thermosetting polymer composites, when contrasted with ferrous, nonferrous, and their respective alloys, offer a broad spectrum of applications. Extensive research has been dedicated to enhancing the intrinsic mechanical and thermal properties of composite materials, with a particular focus on environmentally friendly, recyclable, and biodegradable reinforcements. As a result, the present study involved the preparation of composites by amalgamating cellulose nanofibers (CNFs) sourced from agricultural waste with epoxy to augment the characteristics of polymer composites. The CNFs-reinforced epoxy composites were fabricated via the compression molding process, incorporating filler loadings ranging from 1% to 3% by weight. A comprehensive experimental investigation was conducted on the mechanical properties (tensile, flexural, impact, and hardness) and thermal properties (heat deflection temperature) of these composites. Additionally, scanning electron microscopy was employed to examine the surface characteristics and fractured surfaces of the composites. The results revealed that, among the produced composites, those containing 2 wt% CNFs in the epoxy exhibited superior mechanical properties, outstanding tensile and flexural strengths of 42.8 ± 2 MPa and 106.1 ± 1.6 MPa, respectively, along with an impact strength of 13 ± 2.5 KJ/m² and a hardness rating of 21.2. Notably, these 2 wt% CNFs-reinforced epoxy composites exhibited a 7% increase in the heat deflection temperature, compared to the pristine epoxy resin.

Keywords: red coconut peduncle waste, cellulose nanofibers, mechanical properties, morphology

INTRODUCTION

Increasing environmental concerns have brought into focus the need to minimize the dependence on non-renewable mineral resources for engineered products. Synthetic fibers/fillers are commonly used to reinforce polymer composite structures, typically made of materials such as glass, aramid, and carbon fibers. Moreover, synthetic nanofillers are becoming increasingly important due to their specific properties required in polymer composites. However, despite the widespread use of synthetic fibers/fillers reinforced polymer composite structures in various engineering applications, they have several disadvantages, including high

production costs and significant pollution during production, resulting in potential health hazards.¹ The non-recyclable nature of these synthetic materials poses a significant threat to the environment.²

To address these issues, scientists are shifting their research efforts towards replacing synthetic fibers in composite structures with eco-friendly biodegradable cellulosic fillers at the nanoscale.³ As a result, cellulose nanofibers reinforced biopolymer composites are gaining popularity in various fields, from structural to electronic applications. Cellulose nanofibers (CNFs) in biopolymers are also being used in structural, automotive, electrical, 3D printing, and electronic industries due to their unique properties, including high tensile modulus, large surface area with a network structure, and their non-toxic and eco-friendly nature.^{4,5}

CNFs can be produced from cellulosic materials, such as plant fibers, agricultural waste, rayon cloths, and waste newspapers.⁶ Cellulose nanofiber (CNF) is a fibrous substance with a diameter ranging from 1 to 100 nm and a length that is 100 times or more the diameter. It is obtained through various mechanical processes, such as ball milling, high-pressure explosion homogenization, steam grinding, micro-fluidization, and cryo-crushing.7 CNFs have a web-like structure and contain cellulose, as well as certain amorphous elements. To reduce consumption, energy raw macrocellulosic resources transformed are into pure microcellulosic fibers before CNF extraction.⁸ Among the different mechanical processes, ball milling is a simple and cost-efficient method for producing a large quantity of CNFs from cellulosic macrofibers.9

In a study by Saba et al.,10 CNFs from bleached softwood kraft pulp were used to reinforce polymer composites with varying CNFs filler loadings, and it was found that a 0.75 wt% CNFs loading in the epoxy matrix produced the best tensile (26 MPa) and flexural strength (42 MPa). Similarly, Jahanbaani et al.¹¹ investigated the mechanical properties of spinning-coated CNFs sheets made from wheat straw and epoxyreinforced composites, which exhibited good tensile (117 MPa) and impact strength (202 kJ/m²), compared to lignocellulosic wheat straw fiber-reinforced epoxy composites. Pandurangan et al.¹² analyzed the effect of CNFs on epoxy composites with varving CNFs loading percentages and found that an epoxy composite containing 5 wt% CNFs had improved tensile strength (46.2 MPa) and thermal properties. Kurita et al.4 successfully extracted CNFs using a water jet-based mechanical technique, and the epoxy matrix reinforced with 2.25 vol% CNFs exhibited better tensile strength (74 MPa) and flexural strength (120 MPa), compared to other CNFs loading combinations.

The existing literature indicates that cellulose nanofibers (CNFs) obtained from various mechanical processes can enhance the mechanical and thermal properties of polymer composites. In light of this, Nagarajan *et al.*¹³ conducted research where they successfully isolated CNFs from red coconut peduncle waste using a combination of chemical and ball milling processes. Their efforts resulted in CNFs with favorable physical, thermal, and morphological characteristics. However, it is worth noting that, as of now, there is no published research available on the utilization of CNFs extracted from red coconut peduncle waste as a reinforcement material in epoxy composites.

Recognizing this research gap, the current study aimed to employ CNFs extracted from red coconut peduncle waste as a reinforcement component in epoxy composites, with a specific focus on applications requiring lightweight structural materials. To assess the performance of these epoxy composites, a series of tests were conducted, including tensile, flexural, impact, hardness, heat deflection and dynamic-mechanical analyses. Additionally, field electron-scanning electron microscopy (FE-SEM) was used to examine the morphology of fractured tensile, flexural and impact test specimens. This research seeks to provide valuable insights into the potential of CNFs from red coconut peduncle waste as a sustainable and effective reinforcement for epoxy composites in structural applications.

EXPERIMENTAL Materials

The extraction of CNFs from red coconut peduncle waste (RCPW) was carried out at the Nanotechnology Laboratory (Mechanical Department) situated at Thiagarajar College of Engineering in Madurai, Tamil Nadu, India. The CNFs used in this study were derived through an extraction process outlined in Figure 1 (a-c) and further detailed in Table 1. The properties of the obtained CNFs are summarized in Table 2. The morphology of these CNFs, derived from RCPW using a combination of chemical and ball milling methods, was examined using transmission electron microscopy (TEM). The sample preparation procedure for TEM analysis has been thoroughly described in a prior study.¹³ As depicted in Figure 1 (d), the TEM images clearly illustrate the extracted CNFs as having a weblike structure, with individual CNFs, measuring around 55 nm to 64 nm in width.

The epoxy used in this research was obtained from Javanthee Traders, situated in Chennai, Tamil Nadu, India. Specifically, it was epoxy LY556, which is the diglycidyl ether of Bisphenol-A, and it exhibited a density ranging from 1.15 to 1.2 g/cm³. Additionally, the hardener employed was HY951, an aliphatic primary amine, with a density of 0.97 g/cm³.

Preparation of composites

The compression moulding method was used to prepare epoxy composites with varied CNFs loadings

(1, 2, and 3 wt%). A predetermined amount of CNFs was mixed with epoxy and thoroughly dispersed for 240 minutes using a homogenizer at 10,000 rpm, followed by 10 minutes of sonication to remove air bubbles from the mixture. The hardener was then added to the mixture in a 10:1 (g/g) stoichiometric

ratio (resin: hardener). After that, the mixture was poured into a 30 cm x 20 cm mould. The closed mould was placed in a compression moulding machine and the mixture was cured for a day at a uniaxial compressive pressure of 18 MPa. The prepared composites sheets are shown in Figure 1 (e).



Figure 1: (a-c) extraction process of CNFs, (d) TEM image of CNFs, and (e) prepared composites through compression moulding

Stage No.	Chemical treatment	Process specifics	Treatment outcome
Stage I	Toluene-ethanol (2:1, v/v) at 70 °C for 4 h	Waxy contents are dissolved in toluene-ethanol solution	Pure lignocellulosic fibers are obtained
Stage II	0.7 wt% sodium chlorite at 100 °C for 120 min in an acidic solution	Lignin dissolved in acidified chlorination solution	Remaining hemicellulose coupled cellulose is retrieved
	17.5 wt% /v NaOH solution at room temperature (30 °C) for 35 min	In NaOH solution, hemicelluloses are dissolved	Crude α-cellulose is synthesized
Stage III	80% acetic acid and 70% nitric acid (10:1 ratio) at 120 °C for 15 min	α-Cellulose defibrillation	Cellulose microfiber is synthesized
Stage IV	Ball milling process	Cellulose microfibers are milled for 2 h with 0.6 mm zirconia balls at 850 rpm, at 60:1 ball-to-microfiber ratio	CNFs are obtained

 Table 1

 Chemical treatment and ball milling process, as well as the results of each treatment stage

Type of fiber	Crystallinity index (%)	Crystallite size (nm)	Thermal stability (°C)	Thermal degradation (°C)	Width (nm)	Ref.
CNFs	77.8	6.95	230	325	55-64	13

Table 2 Characteristics of CNFs

Mechanical and thermal characterization

Tensile testing was performed using a UTM machine (Tinius Olsen H10KL) with a 10 kN load cell and a 1.0 mm/min crosshead speed. The tensile characteristics of specimens were determined according to the ASTM D638-10 standard, on samples of 165.0 x 10 x 3.0 mm and the test was carried out with a gauge length of 60 mm.¹⁴ The ASTM D790-10 three-point flexural test was performed with the same machine (127 x 13 x 3 mm) with a cross head speed of 2 mm/min.¹⁵ The impact strength of the composite sheets was evaluated using a Tinius Olsen (Model: 104) in accordance with ASTM D 256-10 (65 mm x 13 mm x 3 mm) standard.¹⁶

The hardness of composite sheets was tested using a Barcol Hardness tester (Model: VBH2) in accordance with ASTM 2583.¹⁷ During the test, the specimens' surfaces were polished to remove scratches. The gap between the pin tip and the edge was kept to a minimum of 3 mm.

An HDT-VICAT tester (XRW300A, Chengde Jinhe Instrument Manufacturing Co., Ltd., Chengde, China) was used to conduct the heat deflection test for measuring the deflection temperature of the composite sheets according to the ASTM D648 (60 mm x 12 mm x 3 mm) standard under the pressure of 1.86 MPa. During the test, silicone oil was utilised as a heat transfer medium with no influence on the mechanical qualities of the specimens.¹⁸ The specimens were heated in an oil bath at a rate of 2 °C/min until deflection was achieved.

For each mechanical and thermal characteristic, an average of five specimens were examined for pristine epoxy and various CNFs filler reinforced epoxy composites as a function of filler loading (wt%). The viscoelastic properties of both pristine epoxy and composite specimens were assessed using an ASTM D4065-01-compliant DMA (Dynamic Mechanical Analysis) Q 800 machine. The testing was conducted in the three-point bending mode, utilizing specimens with dimensions of 65 mm length, 10 mm width, and 3 mm thickness. The oscillation frequency during testing was set at 1 Hz. The temperature range explored during the test spanned from 45 °C to 150 °C, with a controlled heating rate of 5 °C per min.

Fractographic analysis of the composite specimens following tensile, flexural, and impact tests was performed using an FE-SEM instrument, specifically the SUPRA 55 VP-4132 model from Carl Zeiss. The instrument operated within a voltage range from 10 to 30 kV. To prepare the samples for analysis, the fractured regions were initially sectioned into 10 x 10 mm squares. Subsequently, a thin layer of gold coating was applied to these specimens to improve their conductivity for the electron microscopy examination.

RESULTS AND DISCUSSION Tensile testing

In Figure 2a, the tensile strength, measured in MPa, is plotted against varying percentages of CNFs filler in the epoxy resin. The tensile strength of the pristine epoxy measures 31.2±1.7 MPa. Upon the inclusion of CNFs, the epoxy composite achieves its highest tensile strength with a 2 wt% CNFs content, reaching 42.8±2 MPa, and surpassing the strength of the pure epoxy. As shown in Figure 2a, this marks a significant improvement, of 35.4%, in tensile strength, compared to the pure epoxy resin, indicating improved contact and interaction between the CNFs and the epoxy matrix. This enhanced interaction enables more efficient transmission of the applied tensile load.¹⁹ When evaluating the tensile strength, it was observed that, at a 3 wt% CNFs content in the epoxy matrix, there was a decrease of up to 10.7% in comparison to the optimal CNF loading. This decline can be attributed to the agglomeration of CNFs within the epoxy matrix. The agglomeration phenomenon reduces the ability of the composite sheets to effectively transmit stress, leading to a reduction in tensile strength.⁴

As shown in Figure 2b, the tensile modulus of the composite sheets follows a similar trend to the tensile strength. It increases as the CNFs concentration rises to the optimal level. Specifically, for the 2 wt% CNFs-reinforced composite, the maximum tensile modulus reached GPa. 3.62 ± 0.05 This indicates that the reinforcement exhibits excellent stiffness characteristics and adheres well to the epoxy matrix.

However, the tensile modulus drops significantly when the CNFs content exceeds the optimal limit. This decline can be attributed to the deterioration of adhesive strength between the CNFs and the epoxy matrix. The study highlights significant improvements in properties, such as tensile strength and tensile modulus, resulting from the incorporation of organic fillers derived from materials like Cocos nucifera shell, tamarind seed, Polyalthia longifolia seed, and date palm seed into thermosetting plastics.^{17,18,20,21}

Flexural strength tests

In various engineering structural applications, such as pavements, beams and slabs, the

susceptibility to bending is а critical consideration. Hence, the flexural characteristics play a significant role when designing and constructing composites for these purposes. In this study, the addition of up to 2 wt% of CNFs into the epoxy matrix resulted in noticeable increases in both flexural strength (measured in MPa) and flexural modulus (measured in GPa), as illustrated in Figure 3 (a and b).



Figure 3: (A) Flexural strength and (B) flexural modulus of composites

The pristine epoxy exhibited a flexural strength of 82.5 ± 2.28 MPa. When CNFs were incorporated, the flexural strength values for 1 wt%, 2 wt%, and 3 wt% CNFs-reinforced epoxy composites were 99.2 ± 2 , 106.1 ± 1.6 , and 101.5 \pm 2.3, respectively. As depicted in the figure, the highest values for flexural strength and flexural modulus were observed at approximately $106.1 \pm$ 1.6 MPa and 3.9 ± 0.06 GPa, respectively. These values represented an improvement of 36.2% and 37.9%, respectively, compared to the pristine epoxy.

The optimal composite containing 2 wt% CNFs was likely achieved due to the uniform of CNFs distribution and their superior

adhesiveness with the epoxy matrix. Table 3 provides a comparison of the optimal flexural of CNFs-reinforced thermosetting strength composites with that of composites reinforced with other organic fillers. The results indicate that the optimal flexural strength of the CNFsreinforced composite closely aligns with that of composites reinforced with other organic fillers.

Impact strength testing

Impact strength serves as a crucial measure to evaluate the ability of epoxy and its composite materials to withstand sudden applied loads. Figure 4 presents the results of impact tests conducted on pristine epoxy and epoxy sheets containing varying weight percentages of CNFs.

It is worth noting that all CNFs-reinforced epoxy composites exhibited higher impact strength when compared to pristine epoxy, which had an impact strength of $9.1 \pm 1 \text{ kJ/m}^2$. Among the CNFs-reinforced epoxy composites, the lowest impact strength, of $11.1 \pm 1.5 \text{ kJ/m}^2$, was recorded in the case of 1 wt% CNFs-reinforced composites, representing a 22% improvement over the impact strength of pristine epoxy.

The highest impact strength value, amounting to 13 ± 2.5 kJ/m², was achieved by the 2 wt% CNFs-reinforced epoxy composites, marking a substantial 39.1% increase over the impact

strength of pristine epoxy. These results indicate that when CNFs were introduced into the epoxy matrix, they exhibited strong accommodation within the matrix, and the nanostructure of the fillers had excellent wettability. Additionally, the matrix displayed robust bonding properties, enabling enhanced stress transmission between the matrix and the filler.²²

However, it is important to note that, beyond the optimal CNFs content, the impact strength decreased rapidly. This reduction can be attributed to decreased absorption capabilities and a subsequent decrease in the bonding between the matrix and CNFs, reaching a notably low level.



Figure 4: Impact strength of composites

Table 3 Mechanical properties of CNFs reinforced epoxy composite compared with other organic filler reinforced thermosetting composite

Source of organic filler	Matrix	Tensile strength (MPa)	Flexural strength (MPa)	Impact strength (KJ/m ²)	Reference
CNFs from red coconut peduncle	Epoxy	42.8±2	106±1.6	13±2.5	Present study
Wood apple	Epoxy	43.6	78.19	-	Nagaprasad ²⁰ et
Coconut shell	Epoxy	41.3	68.25	-	al., 2019
Bio-char	Epoxy	60	-	10	Karakoti ²³ <i>et al.</i> , 2019
Coconut shell	Vinyl ester	38.70	105.13	33.04	Gnanaraj ¹⁸ et al., 2021
Polyalthia longifolia seed	Vinyl ester	32.5	125	31.09	Stalin ¹⁷ et al., 2020
Date seed	Vinyl ester	40.3	149	17	Nagaraj ²¹ <i>et al.</i> , 2019
Tamarind seed	Vinyl ester	34.3	121	14	Nagaprasad ²⁰ et al., 2019

resistance to cracking, and a fracture mode characterized by crack propagation during the

tensile test of the 1 wt% CNFs-loaded epoxy

composite. Fractures are visible in the matrix (labeled as C) of the fractured specimens, as

shown in Figure 5a.

Morphology of fractured mechanical testing specimens

Figure 5 (a and b) provides insights into the fractured tensile specimens. In Figure 5a, the fractured specimen exhibits a smooth and glassy outer flat surface (labeled as B), indicating a brittle plastic nature, with extremely poor



Figure 5: FE-SEM images of (a) tensile fractured specimen (1 wt% CNFs loading), (b) tensile fractured specimen (2 wt% CNFs loading), (c) flexural fractured specimen (1 wt% CNFs loading), (d) flexural fractured specimen (2 wt% CNFs loading), (e) impact fractured specimen (1 wt% CNFs loading), (f) impact fractured specimen (2 wt% CNFs loading)

S. no	Fractured specimen	Irregular and jagged pattern (A)	Glassy exterior wavy or stream-like pattern (B)	Matrix fracture (C)
1.	Tensile (1 wt% of CNFs loading in epoxy)	Less	High	High
2.	Tensile (3 wt% of CNFs loading in epoxy)	High	Less	Less
3.	Flexural (1 wt% of CNFs loading in epoxy)	Less	High	High
4.	Flexural (2 wt% of CNFs loading in epoxy)	High	Less	Less
5.	Impact (1 wt% of CNFs loading in epoxy)	Less	High	High
6.	Impact (2 wt% of CNFs loading in epoxy)	High	Less	Less

 Table 4

 Characteristics of fractured specimens of 1 wt% and 2 wt% CNFs reinforced epoxy composites

On the other hand, Figure 5b illustrates a fractured surface featuring a high number of uneven and jagged patterns (labeled as A), along with a limited number of glassy external wavy or stream-like patterns (labeled as B), representing the 2 wt% CNFs-loaded epoxy composite. The presence of uneven and jagged patterns suggests that improved CNF dispersion resulted in good interfacial adhesion characteristics between CNFs and the epoxy matrix, enabling better transmission of tensile stress.

This behavior of improved interfacial adhesion and stress transmission is also observed in the tested specimens during flexural and impact tests, as depicted in Figure 5 (c-f). The characteristics of the fractured specimens for both 1 wt% and 2 wt% CNFs-reinforced epoxy composites are summarized in Table 4.

Heat deflection test (HDT)

The Heat Deflection Temperature (HDT) is a critical parameter that indicates the temperature at which a polymer starts to deform under a specified load. Figure 6 displays the HDT values of pristine epoxy and CNFs-reinforced epoxy composite sheets with varying weight percentages.

The HDT value for pristine epoxy was determined to be 210±4.5 °C. Notably, the HDT values exhibited a rapid increase as different weight percentages of CNFs were introduced into the epoxy matrix. Importantly, when considering filler contents ranging from 1 to 3 wt%, the maximum HDT value was achieved by the 2 wt% CNFs-reinforced epoxy composites, reaching 224.2±3.8 °C. It is evident that the HDT value improved with the inclusion of CNFs content.

These findings underscore the superior thermal properties of CNFs when compared to other natural fillers commonly used in reinforced thermosetting composites. For instance, CNFs-reinforced epoxy composites exhibit significantly higher HDT values than those reinforced with tamarind seed (71 °C), date seed (84 °C), *Polyalthia longifolia* seed (66 °C), and coconut shell (171 °C). This demonstrates the potential of CNFs as a valuable reinforcement material for enhancing the thermal stability of epoxy composites.^{17,18,20,21}

The slight decrease in the HDT value observed in the case of the 3 wt% CNFs reinforced epoxy $(219.2\pm 3.1 \text{ °C})$ suggests that the bonding between the CNFs and the epoxy may not be as stable at this higher filler content. However, it is important to note that this decrease in HDT is still within a relatively high temperature range, indicating that the thermal stability of the composite is not significantly compromised. The HDT value remains quite robust, emphasizing the overall effectiveness of CNFs as a reinforcement material for enhancing the thermal properties of the epoxy composite.

Hardness testing

Figure 7 presents the Barcol hardness values of both the pristine epoxy resin and various weight percentages of CNFs-reinforced epoxy composites. The pristine epoxy exhibited a hardness value of 19.67 ± 0.5 . However, when 2 wt% CNFs were added, the hardness value significantly increased to 21.2 ± 1.5 . This enhancement can be attributed to the even dispersion of CNFs, which results from proper mixing proportions. It leads to strong adhesive bonding between the matrix and the reinforcement, especially when the optimal CNFs content is added.^{23,24}

Remarkably, both the pristine epoxy and the 3 wt% CNFs-reinforced epoxy composite exhibited a hardness value of around 20 ± 1.7 , as depicted in Figure 7. This suggests that the addition of 3 wt%



Dynamic analysis

Dynamic mechanical analysis was employed to examine the viscoelastic properties of both unmodified epoxy and epoxy composite loaded with an optimal 2 wt% of CNF under dynamic loading conditions. In Figure 8 (a and b), the curves for loss modulus illustrate the differences between pure epoxy and epoxy composites reinforced with CNFs.

At room temperature, the storage modulus for pristine epoxy stands at 1500 MPa, while the epoxy composite with 2 wt% CNF reinforcement reaches 2095 MPa, marking a substantial 39% increase compared to pristine epoxy. However, as depicted in Figure 8a, the storage modulus of both unmodified epoxy and 2 wt% CNF-reinforced composites decline as the temperature rises. This decline is evident in three distinct states: the glassy (solid) state, the transitional state, and the rubbery state (Fig. 8a).

A glassy state was identified within the temperature range from 40 °C to 78 °C for pristine epoxy and from 40 °C to 87 °C for the epoxy composite reinforced with 2 wt% of CNFs. In this state, characterized by limited molecular mobility within the polymer chains, the storage modulus exhibited a continuous and gradual decrease. Notably, the storage modulus of the 2

CNFs resulted in inappropriate bonding because of insufficient matrix material. Additionally, it increased the porosity of the composites, which consequently led to a lower hardness value. This heightened hardness value contributes to improved wear resistance in the composites and renders them suitable for use in dynamic loading conditions.



wt% CNFs-reinforced composite in the glassy state exceeded that of pure epoxy.

Figure 8a illustrates that the epoxy composite with 2 wt% CNFs displayed a higher storage modulus in the glassy state, below its glass transition temperature (Tg). This enhancement can be attributed to the binding interactions between the nano-fillers and the matrix, a phenomenon discussed above during the analysis of tensile testing results.

The transition state was marked by a sudden decrease in the slope of the storage modulus as the temperature increased, occurring between 84 °C to 112 °C for pristine epoxy and 90 °C to 107 °C for 2 wt% CNFs-reinforced epoxy composites, following the conclusion of the glassy state. During this stage, the specimens underwent plastic deformation, leading to an increase in free volume due to heightened viscosity (segmental mobility) of the epoxy molecules. This resulted in a physically softer epoxy matrix and a reduction in interfacial bonding between the CNFs and the epoxy matrix.²⁵

Towards the end of the transition stage, there were no significant variations in the storage modulus in the rubbery state for both pristine epoxy and the epoxy composite reinforced with 2 wt% CNFs.

As depicted in Figure 8b, the loss modulus values for both pristine epoxy and the optimally loaded (2 wt%) CNFs epoxy composites exhibit an initial increase until reaching the glass transition temperature, followed by a subsequent decrease. Notably, the loss modulus curve for the 2 wt% CNFs-reinforced epoxy composite covers a broader range and exhibits a higher peak, with a maximum loss modulus of 247 MPa, as observed in comparison to the curve for pristine epoxy. Furthermore, this curve shifts towards the righthand side. This behavior can be attributed to the uniform dispersion of CNFs within the epoxy matrix and the immobilization of matrix segments at the surface of the CNFs. Similar findings have been reported in previous literature concerning polymer composites reinforced with cellulosic fillers.²⁶⁻²⁸

In conclusion, both pristine epoxy and 2 wt% CNFs-reinforced epoxy demonstrate the highest loss modulus values, indicating increased mechanical energy dissipation. However, beyond the glass transition temperature, the loss modulus values gradually decline with increasing temperature, primarily due to the softening of the matrix material, as illustrated in Figure 8b.

The integral of the tan (delta) curve signifies the degree of molecular mobility within the polymer and consequently, the damping behaviour of both the pristine epoxy and its composite. This damping factor undergoes a significant increase with rising temperature, reaching its peak at the conclusion of the transition state for both pristine epoxy and 2 wt% CNF-reinforced epoxy, as illustrated in Figure 8c. Notably, when compared to pure epoxy, the 2 wt% CNF-reinforced epoxy composite exhibits the lowest damping factor at the end of the transition region due to the constrained movement of polymer chains.



Figure 8: (a) Storage modulus, (b) loss modulus, and (c) tan delta curve of pristine epoxy and 2 wt% CNF reinforced epoxy composite

Moreover, the glass transition temperature (Tg) experiences an elevation in the case of the 2 wt% CNF-reinforced epoxy composite,

surpassing that of pristine epoxy by approximately 13%. This improvement is attributed to the influence of CNFs, coupled with

their uniform dispersion and strong interfacial interaction with the epoxy matrix, which enables the storage of load energy rather than its dissipation, thus augmenting the Tg of the CNFreinforced epoxy composite. Subsequently, Tg decreases, and the loss modulus curve follows a similar pattern.

CONCLUSION

CNFs were extracted from red coconut peduncle waste and were used as a reinforcing material in the production of epoxy composites. The tensile, flexural, impact, hardness and heat deflection assessments were carried out to analyse the performance of CNFs manufactured epoxy composites, compared to pristine epoxy composite. The results of the study revealed that the 2 wt% CNFs reinforced epoxy composite exhibited the maximum tensile strength and tensile modulus (42.8 \pm 2 MPa and 3.62 \pm 0.05 GPa, respectively), the highest value of flexural strength and flexural modulus (106.1 \pm 1.6 MPa and 3.9 ± 0.06 GPa, respectively), the highest impact strength $(13 \pm 2.5 \text{ kJ/m}^2)$ and the maximum HDT value (224.2 °C), along with a hardness value of 21.2. SEM analysis confirmed the better dispersion of CNFs in the epoxy composite with 2 wt% of CNFs loading. DMA analysis showed that the storage modulus and glass transition temperature were enhanced for the 2 wt% CNFs reinforced epoxy composite, when compared to the pristine epoxy.

Based on the research findings presented above, it can be concluded that the incorporation of 2 wt% CNFs in epoxy is considered optimal for a range of industrial structural applications. These applications may include the construction of partition walls, door panels, window frames, and similar structural components. The research suggests that this 2 wt% of CNF reinforcement enhances the mechanical properties and thermal behavior of epoxy composites, making them wellsuited for use in these industrial contexts.

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