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Effect of Multi-Walled Carbon Nanotubes on the Mechanical and Thermal Properties of Curauá Natural-Fiber-Reinforced Composites

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Abstract: The main objective of this research centered on investigating the effect of the addition of multi-walled carbon nanotubes (MWCNTs) on the mechanical and thermal properties of curauá-fiber-reinforced composites. The MWCNTs were added either to the fiber surface or into the resin matrix as the second reinforcing phase. The MWCNT-modified curauá fibers as well as raw fibers were characterized using a single-fiber tensile test, TGA, and FTIR analysis. Further, different composite samples, namely, pure curauá, (curauá + MWCNTs) + resin and curauá+ (resin + MWCNTs), were manufactured via compression molding and tested to determine their mechanical and thermal properties. Scanning electron microscopy (SEM) analysis was used to examine the surfaces of the tested fibers. It was found that the addition of MWCNTs to the curauá fibers resulted in positive effects (an enhancement in properties was found for the MWCNT-modified fibers and their composites). The addition of MWCNTs also increased the thermal stability of the natural fibers and composites.

Keywords: multi-walled carbon nanotube (MWCNT); composites; curauá fiber

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1. Introduction

Natural fibers present advantages due to their many positive characteristics, such as biodegradability, low density, and low cost, when compared to synthetic fibers. However, their main drawbacks are high variance in fiber quality and the absorption of humidity as a function of the hydrophilic characteristic of the fiber, leading to low interfacial adhesion between the fiber and the hydrophobic matrix and thus weak mechanical properties [1–3]. Researchers have used different techniques to overcome these shortcomings (i.e., chemical treatments of the fibers and hybridization techniques) [4,5].

One technique explored in the literature for improving the properties of natural fiber-reinforced composites is the use of filler materials (either on the fiber surface or inserted into the matrix as a second reinforcing phase) [6–8]. Due to their remarkable attributes, including a high specific surface area, strong chemical compatibility with the hydrophobic matrix, and the ability to arrest cracks, they have a synergistic relationship with natural-fiber-reinforced composites (NFRCs) [9]. However, to prevent undesirable filler agglomeration, it is imperative to meticulously assess the fabrication process and the homogenization technique employed for the matrix/filler combination [10,11].

Carbon nanotubes (CNTs) may be used as multi-scale reinforcements for this purpose and mainly fall into three categories: single-walled carbon nanotubes (SWCNTs), double-walled carbon nanotubes (DWCNTs), and multi-walled carbon nanotubes (MWCNTs) [12,13]. MWCNTs are highly utilized in the modification of polymer composites.

These nanotubes consist of multiple layers of rolled graphene sheets, offering exceptional mechanical, electrical, and thermal properties. Due to their unique structure and high aspect ratio, MWCNTs are widely employed as reinforcing agents to enhance the performance and functionalities of polymer composites in various applications [14]. However, a significant challenge in attaining optimal performance lies in the inherent tendency of MWCNTs to agglomerate, resulting in inadequate dispersion within the composite, which can have a detrimental effect on the overall performance and mechanical properties of the composite structures.

Several authors have explored the effect of MWCNTs on the mechanical and thermal properties of composites [11,12,15–18]. Zhao et al. [16] investigated the influence of MWCNTs when mixed into the matrix and fiber of carbon-fiber-reinforced composites. It was found that the mechanical properties (tensile, flexural, and short-beam strength) enhanced with the mixture of the nanotubes in the matrix and fiber. Furthermore, the most promising results were found for the case of adding MWCNTs in the fiber. The incorporation of MWCNTs resulted in an enhancement in the thermal properties of the composites, as evidenced by the improved glass transition temperature observed when MWCNTs were added to the resin. Dilfi et al. [18] analyzed the effect of MWCNTs in ramie-fiber-reinforced composites using two types of chemical treatments, alkaline and silane, to facilitate the coupling of the nanotube with the fiber and reported that the incorporation of nanotubes in the composites led to a significant enhancement in the mechanical and thermal properties of these materials. Pulikkalparambil et al. [17] investigated the effect of Graphite (Gr) nanoparticles in bamboo-fiber-reinforced composites. The composites studied were bamboo-fiber-reinforced composite (EP/BF), bamboo-fiber-reinforced composite + 1 wt% of Gr (EP/BFGr1), bamboo-fiber-reinforced composite + 3 wt% of Gr (EP/BFGr3), bamboo-fiber-reinforced composite + 5 wt% of Gr (EP/BFGr5), and bamboo-fiber-reinforced composite + 10 wt% Gr (EP/BFGr10). It was found that the mechanical properties (tensile and flexural strength and hardness) were improved by the addition of nanoparticles. However, this improvement was only obtained at an up to 5% of addition of the nanoparticles; after reaching this limit, the properties were impaired by the process of the agglomeration of the nanoparticles. Moreover, the study reported that the addition of nanoparticles led to an increase in the thermal stability of the composites.

In their research, Prabhudass et al. [19] investigated the integration of multi-walled carbon nanotubes (MWCNTs) into NFRCs. Their findings revealed that the hybrid composite, enhanced with MWCNTs, displayed notable enhancements in both its glass transition temperature (T_g) and storage modulus (E′). Notably, the incorporation of MWCNTs led to a remarkable 41% increase in the storage modulus (E′), highlighting their substantial influence on the material's performance.

Neto et al. [11] conducted a comprehensive study investigating the impact of MWCNTs on the UV- and water-spray-aging process of natural fiber and hybrid composites. The hybrid composites were composed of plain weave bidirectional fabrics made from a combination of jute and glass fibers embedded in an epoxy resin matrix. The fabrication of composite plates was accomplished using the compression-molding technique. The process began with manually mixing the fillers with the resin, followed by a sonication step at 100 W. The filler weight fraction was maintained at 0.6%. To assess the mechanical properties, tensile and flexural tests were performed in accordance with ASTM standards. The samples were subjected to aging conditions for 500 h and 1000 h, respectively. It was observed that the neat natural fiber composites presented enhanced mechanical properties. Yet, for hybrid composites, a small decrease in both tensile and flexural strength was found.

While numerous studies have investigated the influence of carbon nanotubes on mechanical and thermal properties, such an influence has not been fully explored for natural-fiber-reinforced composites. Therefore, the main objective of this research was to analyze the effect of MWCNTs on the mechanical and thermal properties of curauá natural fibers and their composites. MWCNT-coated natural fibers were fabricated, and fiber-reinforced composites were developed using two different methods of filler reinforcement.

These methods included the direct coating of MWCNTs onto the fibers and incorporating MWCNTs into the resin matrix prior to composite fabrication. A tensile test and TGA analysis were used to measure the mechanical and thermal properties of the individual curauá fibers (coated with MWCNTs and without MWCNTs). Tensile and flexural tests were used to measure the mechanical properties of the composites, while TGA was used to measure the thermal properties of the composites. Scanning electron microscopy (SEM) analysis was used to assess the surfaces of the tested fibers.

2. Materials and Methods

2.1. Materials

The Curauá fibers used in this study were supplied in natura by the Federal Rural University of Amazonia (UFRA, Amazônia, AM, Brazil). The bicomponent epoxy resin HEX 135 SLOW, supplied by Barracuda Advanced Composites (Rio de Janeiro, RJ, Brazil), was used as a matrix. The multi-walled carbon nanotubes (MWCNTs) were purchased from Nanostructured & Amorphous Materials, Houston, TX, USA.

2.2. Specimen Preparation

MWCNT-coated curauá fibers were fabricated, and fiber-reinforced composites were developed using two different methods of filler reinforcement. These methods included the direct coating of MWCNTs onto the curauá fibers and incorporating MWCNTs into the resin matrix prior to composite fabrication.

2.2.1. MWCNT-Coated Natural Fibers

The curauá natural fibers were coated with MWCNTs (see Figure 1) using the following procedure. First the fibers were dried in an oven for 1 h at 80 °C. After this step, the natural fibers were immersed in a solution of distilled water (100 mL) containing carbon nanotubes for 1.5 h and mixed via the sonification process. Furthermore, the fibers were dried again for 1.5 h at 100 °C.

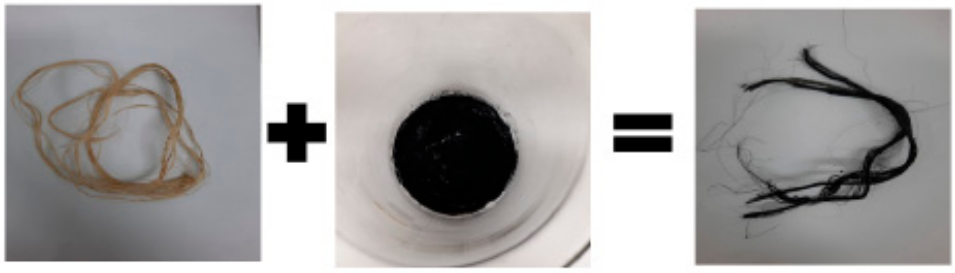


Figure 1. Schematic of the process of coating curauá fibers with MWCNTs.

2.2.2. MWCNT-Modified Composites

The fabrication processes for curauá + (MWCNT + resin) and (curauá + MWCNT) + resin composite specimens were as follows: the MWCNTs were first added to neat epoxy resin and mixed manually for a few minutes. Next, the fillers were dispersed in the matrix via the ultrasonication technique. The percentage of MWCNTs added (0.6 wt%) and the dispersion procedure followed the author's previous work [20]. The composites were manufactured via compression molding, utilizing a heated plate hydraulic hot press (Solab SL 20, São Paulo, Brazil) in conjunction with a steel mold for curing. Specimens were subsequently cut from the composite plates using a tungsten carbide blade in accordance with the geometric specifications outlined in the ASTM D3039 international standard for tensile tests and ASTM D790 for flexural tests.

2.3. Test Methods

2.3.1. Fourier-Transform Infrared Spectroscopy (FTIR)

The FTIR technique was used to investigate the possible influences of MWCNTs on the functional groups of the curauá fibers. The Spectra-Two model spectrophotometer (Perkin Elmer, Forest Hill, LA, USA) for FTIR spectroscopy available at Pontifical Catholic University of Rio de Janeiro (PUC-Rio) was used. For all samples, the same mass quantities of 2 mg of fiber were used.

2.3.2. Single Fiber Test

Curauá single fibers were characterized under quasi-static tension according to the ASTM C1557 international standard. To fabricate the specimens, an 80 by 40 mm paper template was utilized, with the curauá fiber securely fixed with the aid of a fast-curing cyanoacrylate adhesive. Afterwards, adhesive tape was attached to the ends of the paper to facilitate its attachment to the testing machine. In total, fifteen specimens were fabricated and tested. It is noteworthy that the reduced specimen dimensions are a result of the challenge of obtaining single fibers of the correct length. The testing was conducted using an Instron® 5966 universal testing machine, which was equipped with a 1 kN load cell and operated at a test speed of 0.2 mm/min (Norwood, MA, USA).

2.3.3. Tensile and Flexural Tests

The universal Instron® 5966 (Norwood, MA, USA) machine with a 10 kN load cell, available at the Laboratory of Adhesive and Composite Materials (LADES) of CEFET/RJ, Rio de Janeiro, Brazil, was used for the tensile and flexural tests. Five samples for each case were tested according to the ASTM D3039 and ASTM D790 standards, with a test speed of 1 mm/min.

2.3.4. Thermogravimetric Analysis (TGA)

TGA was performed in a NETZSCH TG 209 F3 Tarsus machine (Netzsch-Gerätebau GmbH, Wiesbaden, Germany). Samples weighing approximately 8–10 mg for the fiber samples and 20–30 mg for composite samples were used to take measurements. An alumina (Al_2O_3) crucible was used. Each sample was tested in the temperature range of 30–600 °C at a constant heating rate of 10 °C/min under a nitrogen atmosphere (20 mL min^{-1}).

2.4. SEM Analysis

Quanta FEG 450 microscope (used at an acceleration level of 10KV) available at Nanotechnology Characterization Laboratory (CENANO) of the National Institute of Technology (INT), Rio de Janeiro, Brazil, was used for the SEM analysis of the surfaces of the fibers. All samples were coated with a platinum layer with a surface density equal to 21.53 g/cm^3.

3. Results and Discussion

3.1. Mechanical and Thermal Properties of Fibers

3.1.1. FTIR

The curauá fiber and MWCNT-modified curauá fiber were characterized using FTIR spectroscopy to confirm the reactions occurring between the MWCNTs and curauá fiber, and the resulting spectra are shown in Figure 2. The curauá fiber presented the following absorption band spectrum for lignocellulosic materials: cellulose (3327, 2905, 1636, 1318, 1012, and 894 cm^{-1}), lignin (1603, 1510, 1423, 1364, and 1248 cm^{-1}), and hemicelluloses (1724, 1154, and 1021 cm^{-1}) [18,21].

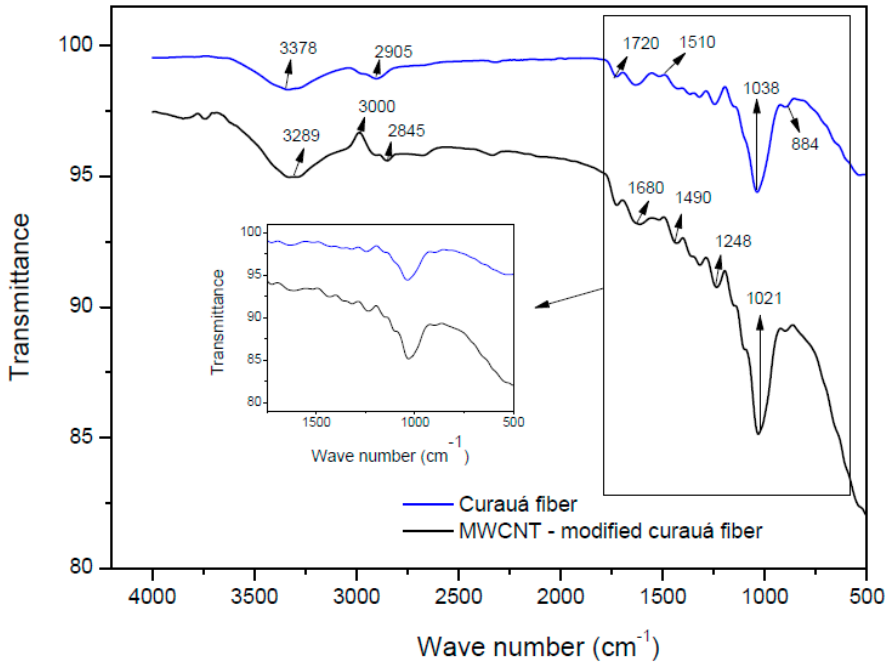


Figure 2. FTIR spectra of Curauá fiber and MWCNT-modified Curauá fiber.

The absorption bands within the Curauá fiber spectrum are as follows:

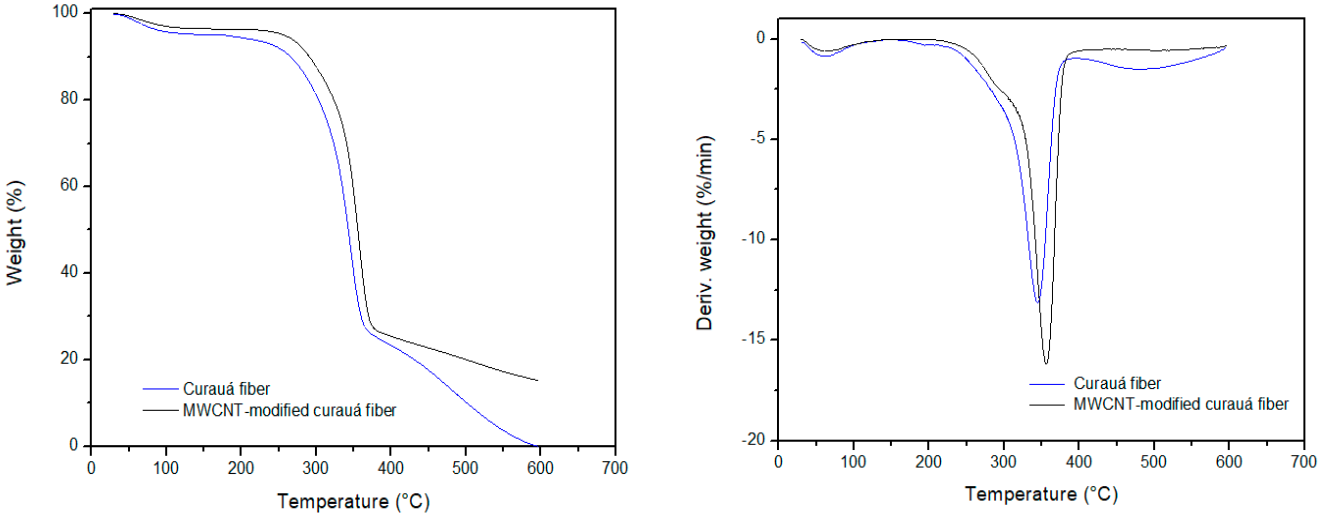
- At 3379 cm^{-1}, there is a band corresponding to the elongation of OH groups found in cellulose and water;
- The band at 2916 cm^{-1} is attributed to the symmetrical and asymmetrical stretching of the aliphatic chain (C–H);
- At 1736 cm^{-1}, there is a band corresponding to the elongation vibration of the carbonyl group (C=O);
- At 1430 cm^{-1}, there is a band is associated with the aliphatic C–H vibration;
- At 1110 cm^{-1}, there is an absorption band attributed to the elongation vibration of the ether groups [22];
- Other bands corresponding to the existence of a high content of oxygen functional groups on the MWCNT surface, such as (–C–O–C) groups like structural oxides and oxygen bridges, to name a few, are evident in the multiwall carbon nanotube FTIR transmission spectra [23].

Owing to the functionalization process, there was a decreasing relative intensity of the –OH water-associated band (3289 cm^{-1}), and a rise in an additional peak (near 3000 cm^{-1}) confirmed the presence of various hydroxyls on the carbon surface. Moreover, the decrease in the intensity of the peaks corresponding to the -OH stretching and bending vibrations also suggested that CNTs had been grafted onto the surface of the curauá fiber. The peaks observed at 1688 cm^{-1} and 1490 cm^{-1} in the MWCNT– modified curauá fiber cases were due to the carbon skeleton vibrations of MWCNT [23]. These findings indicate that there were alterations in the relative intensities of certain bands, indicating a possible connection between the MWCNT molecules and functional groups mentioned earlier. This connection seems to have caused a significant reduction in the intensities observed throughout the spectrum. The experimental results demonstrate notable variations in the relative intensities of specific bands, suggesting a potential binding interaction between the MWCNT molecules and the functional groups. These interactions appear to have induced a substantial attenuation in the overall intensity of the spectrum.

3.1.2. Thermal Properties of Fibers

TGA analysis was employed to examine the impact of nanotube application on the thermal stability and decomposition behavior of the investigated fibers. Curauá fiber and

MWCNT-modified curauá fibre specimens were analyzed, and the results are presented in Figure 3a,b and Table 1. The initial decomposition temperature (T_{IDT}), final decomposition temperature (T_{FDT}), derivative thermogravimetric temperature (T_{DTG}), and char residue were extracted from the TG and DTG curves for each case studied. These parameters describe the thermal stability of the composites [24]. The curauá fiber presented a mass loss at $T_{(100°C)}$ higher than that of the MWCNT-modified curauá fiber, with the respective values of 4.22% and 2.96%. The literature shows that between 60 and 150 °C, the evaporation of moisture retained in natural fiber takes place [24]. On the other hand, the T_{IDT} of the MWCNT-modified curauá showed an increase in thermal stability when compared to the unmodified curauá fiber, i.e., 331 °C and 313 °C, respectively (see Figure 3a). Finally, the residual rate of the MWCNT-modified curauá indicated a considerable increase due to the presence of MWCNTs (Table 1).



(**a**) (**b**)

Figure 3. Thermogravimetric analysis data for the curauá fiber: (**a**) TG curves; (**b**) DTG curves.

Table 1. TGA analysis data.

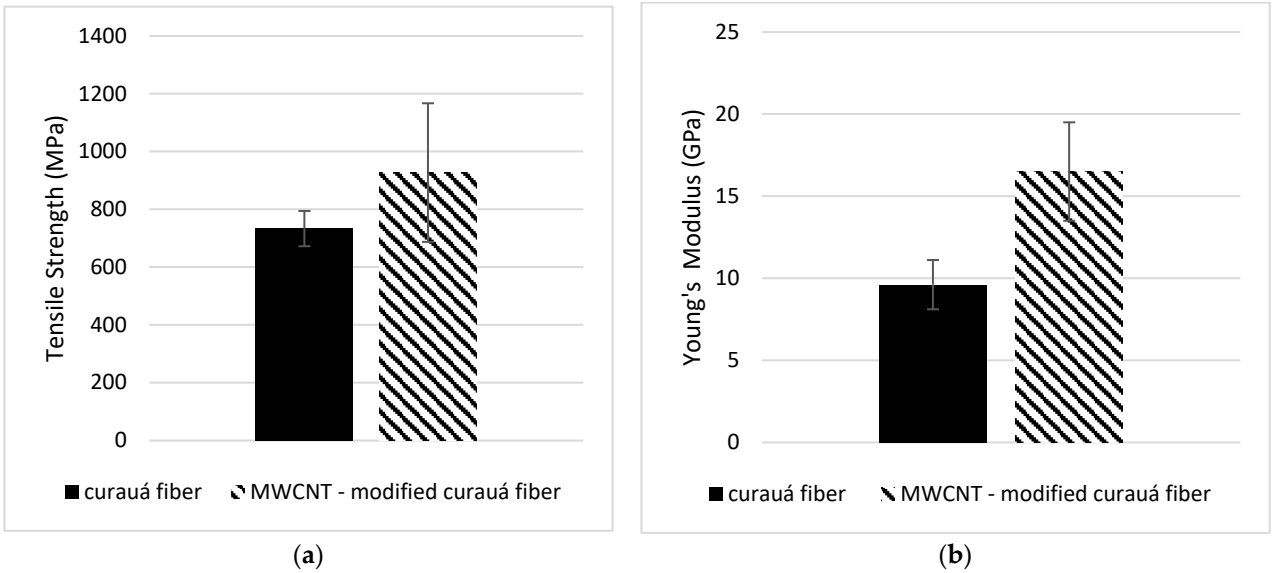
Fiber	$T_{(100°C)}$ (%)	T_{IDT} (°C)	T_{FDT} (°C)	Residual Mass (%)	T_{DTG} (°C)
Curauá	4.22	313.1	359.8	0.04	344.8
MWCNT-modified curauá	2.96	331.1	369.5	15.2	356.3

3.1.3. Single Fiber Test

The curauá fibers studied here showed a high tensile strength (733 MPa) and Young's modulus (9.61 GPa). These values are in line with values from the literature. For instance, in their study, Martel et al. [25] investigated the performance of curauá fibers under both natural and treated conditions, aiming to enhance their durability and mechanical properties. They reported a range of tensile strengths from 326 to 872 MPa, with Young's modulus values ranging from 5.8 to 16.5 GPa. In the work conducted by Neves et al. [26], tensile strength and Young's modulus were examined for curauá fibers of varying lengths (10–40 cm). For fibers with a length of 40 mm, they recorded a tensile strength of 566 ± 76.7 MPa and a Young's modulus of 38.7 ± 5.0 GPa. Additionally, the authors of another study [27] reported values of 825 MPa for tensile strength and 9 GPa for Young's modulus.

The addition of MWCNT nanoparticles affected the tensile properties of the curauá fibers (Figure 4a,b). It can be seen that the MWCNT-modified curauá fibers showed an increase in tensile strength of approx. 26% and an increase of approx. 71% in Young's modulus when compared to unmodified curauá fiber. This can be attributed to the strong

adhesion of MWCNTs to the curauá fiber surface, with the MWCNTs forming bonds with numerous individual fiber fibrils, as can be seen in Figure 9b. Lima et al. [28] showed that different natural fibers have different characteristics, such as lumen size, wall thickness, cell quantities, and chemical treatment effectiveness. These factors affect the mechanical properties of these materials. It was shown in the literature that curauá fibers with a smaller lumen diameter and a higher percentage of cellulose present better performance than jute, sisal, and rami fibers [21,29,30].



(**a**) (**b**)

Figure 4. Tensile data on natural fiber as a function of MWCNT coating: (**a**) tensile strength and (**b**) Young's modulus.

3.2. Mechanical and Thermal Properties of Composites

3.2.1. Thermal Properties

TGA analysis was conducted to assess how the addition of nanotubes influenced the thermal stability and decomposition process of the studied composites. The initial decomposition temperature (T_{IDT}), final decomposition temperature (T_{FDT}), and char residue of the examined composites were derived from the TG curves for each case. These parameters describe the thermal stability of the composites, and the results are presented in Figure 5a,b and Table 2. At $T_{(100°C)}$, the unmodified curauá fiber composite specimens presented a higher mass loss (1.04%) compared to the (curauá + MWCNT) + resin (0.46%) and curauá + (resin + MWCNT) specimens (0.96%). It was shown in the literature that between 60 and 150 °C, the evaporation of moisture retained in the natural fiber takes place [24]. The incorporation of MWCNTs in composites helps to reduce the voids between the fiber–matrix interfaces, limiting composites' water absorption capacity.

Table 2. TGA analysis data for the composites studied.

Composite	$T_{(100°C)}$ (%)	T_{IDT} (°C)	T_{FDT} (°C)	Residual Mass (%)	T_{DTG} (°C)
Curauá	1.04	304.3	369	11.26	338.6
(Curauá + MWCNT) + resin	0.46	331.1	388.6	14.43	362.2
Curauá + (resin + MWCNT)	0.96	326.8	389	17.50	355.8

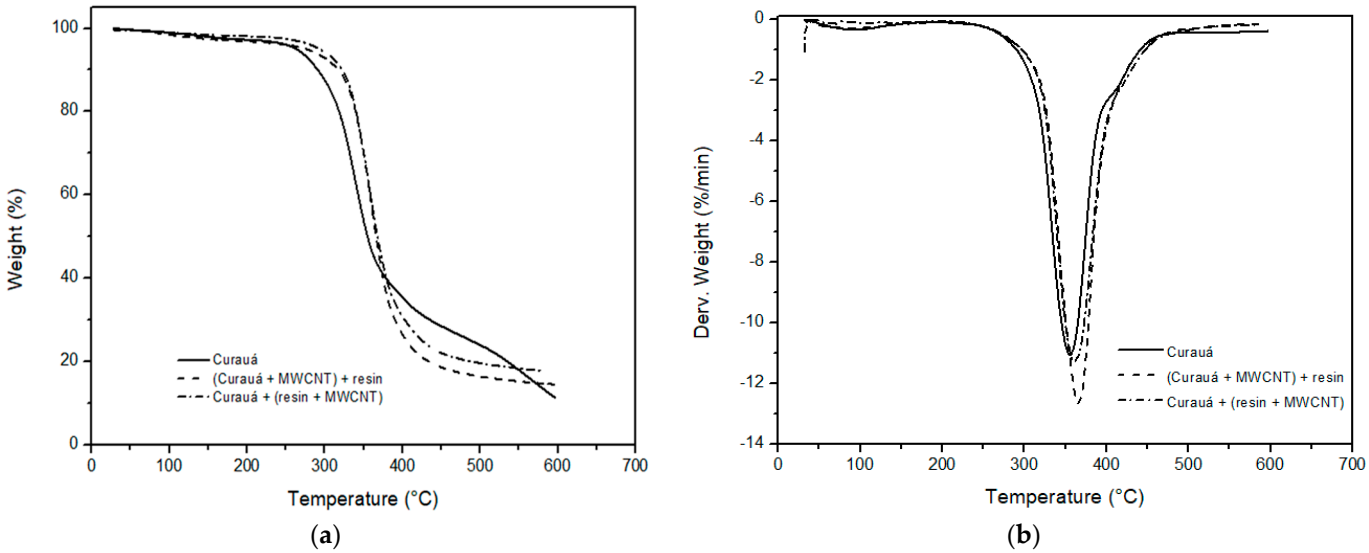


Figure 5. Thermogravimetric analysis data for the curauá fiber composite: (**a**) TG curves; (**b**) DTG curves.

The addition of MWCNTs to either the fiber surface or into the resin matrix of the composites as a second reinforcing phase increased the maximum degradation temperature when compared to the pure curauá composite specimens, as expected. For instance, the values of T_{IDT} for the curauá + (resin + MWCNT) and (curauá + MWCNT) + resin composite samples were 326.8 °C and 331.1 °C, respectively, and are higher compared to this value for the unmodified curauá fiber composite specimens (304.3 °C). This result is in accordance with the literature, indicating that nanotubes improve the thermal characteristics of composites [31].

Another noteworthy aspect is the notable rise in residual mass observed in the MWCNT-filled composites when compared to the unmodified samples. This increase can be attributed to the incorporation of particles within the composites, with the residual mass percentage reaching 11.26% for the unmodified curauá fiber composite, 14.43 for (curauá + MWCNT) + resin, and 17.50 for the curauá + (resin + MWCNT) specimens.

Finally, the DTG curve highlights the peak rate of thermal decomposition, with each degradation stage corresponding to the constituents of the fibers. In the case of the curauá fiber composites, their degradation process consists of three distinctive stages. The initial stage involves the loss of moisture from the natural fiber (occurring between 60 and 100 °C). Subsequently, the second stage is characterized by the decomposition of the primary fiber constituents, including hemicellulose, cellulose, and lignin, within the temperature range of 200–500 °C. Lastly, the last degradation stage results in the formation of active char as a residual byproduct. The value of DTG (°C) was 338.6 for the unmodified curauá fiber composite specimens, while these values for the (curauá + MWCNT) + resin and curauá + (resin + MWCNT) specimens were 362.2 and 355.8, respectively.

3.2.2. Mechanical Properties

Tensile Test

Figure 6 shows representative tensile stress–strain curves of the composites studied. Using these curves, the tensile properties (tensile strength and Young's modulus) were calculated, and they are summarized in Table 3.

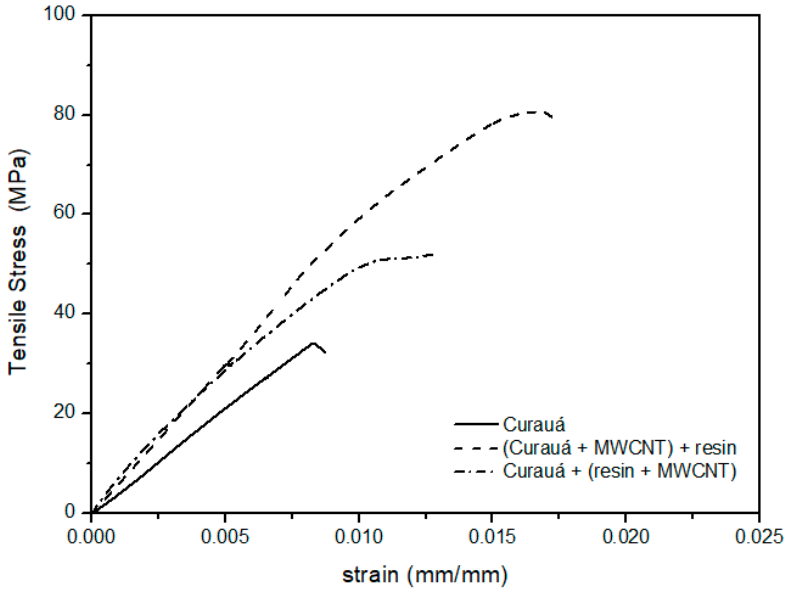


Figure 6. Representative tensile stress–strain curves of the composite specimens.

Table 3. Tensile test data.

Composite	Tensile Strength (MPa)	Young's Modulus (GPa)
Curauá	44.23 ± 7.20	4.95 ± 0.51
(Curauá + MWCNT) + resin	80.62 ± 8.45	7.60 ± 1.06
Curauá + (resin + MWCNT)	52.59 ± 5.29	6.80 ± 0.97

It can be seen that the (curauá + MWCNT) + resin composites presented an increase of approx. 54% in tensile strength when compared to the unmodified curauá composite specimens, while the curauá + (resin + MWCNT) composites presented an increase of approx. 19%. This can be explained by the fact that the roughness of the curauá fiber observed via SEM (see Figure 9) positively influenced the tensile properties of the (curauá + MWCNT) + resin specimens. In addition, the MWCNTs lie on the fiber side of the fiber–matrix interface, which is significantly stiffened and toughened [32,33]. Moreover, previous studies have demonstrated that introducing MWCNTs into the matrix reduces the voids between the fiber–matrix interface, thereby enhancing the load transfer mechanism between the reinforcement and the matrix [34].

Similar to tensile strength, the Young's modulus was also positively affected by the addition of nanoparticles. For instance, the (curauá + MWCNT) + resin and curauá + (resin + MWCNT) composites showed an increase in Young's modulus of approx. 54% and 37% when compared to the unmodified curauá composite specimens. Yan et al. [35] observed that carbon nanotubes exhibit robust adhesion to fiber surfaces and can penetrate the interstitial spaces between the fibrils within the fibers. Additionally, the interaction between fibers and nanotubes is reinforced by Van der Waals forces and the expansion effect, as highlighted in previous research [34].

Flexural Test

Figure 7 shows representative flexural stress–strain curves of the composite studied. From these curves, the flexural properties (flexural stress and flexural modulus) of the composites were calculated, and they are summarized in Figure 8a,b.

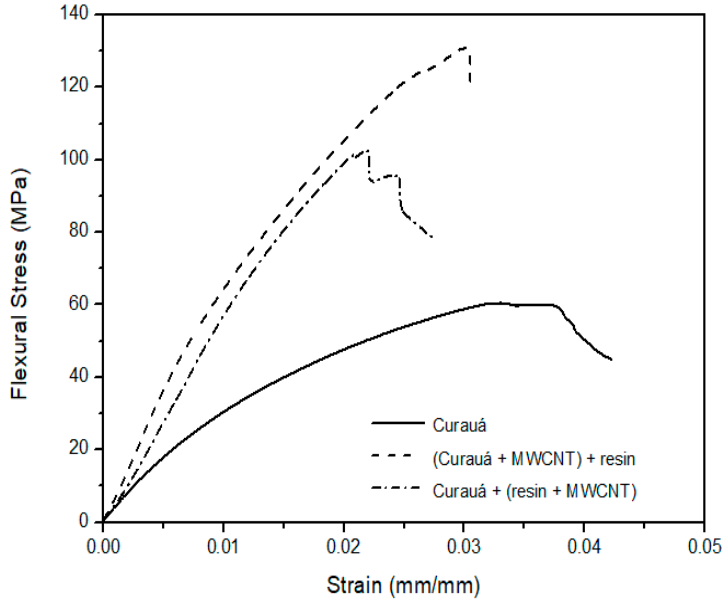
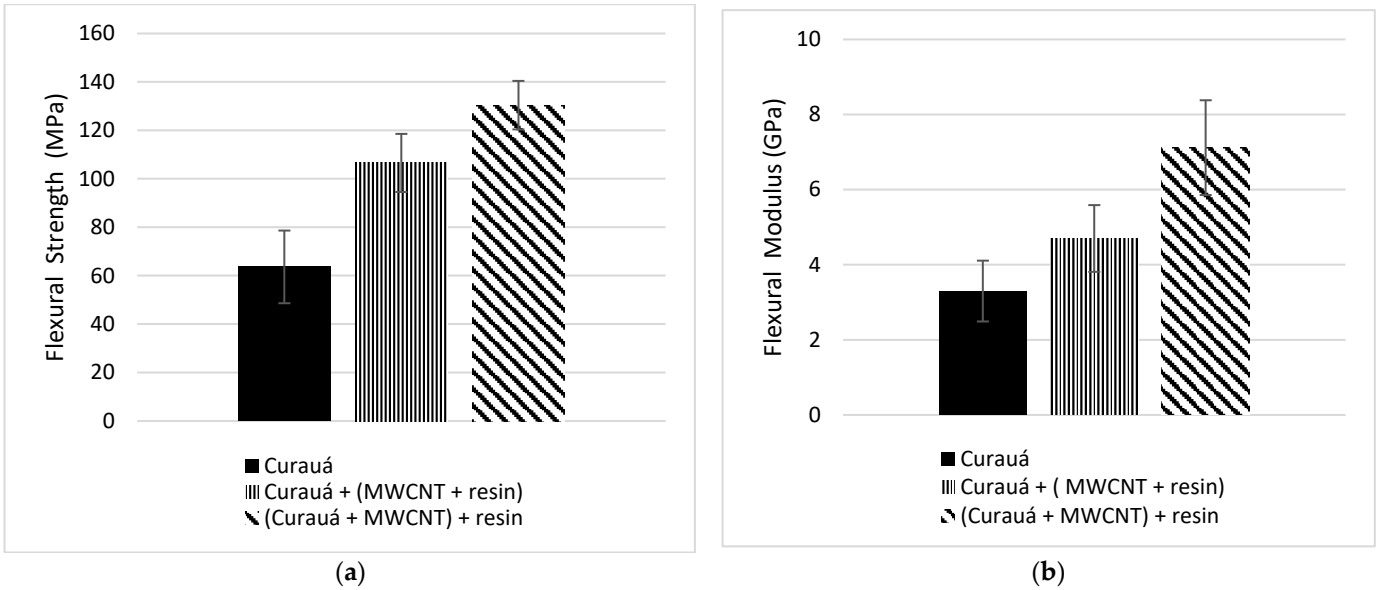


Figure 7. Representative flexural stress–strain curves of the curauá fiber composite specimens.



(**a**) (**b**)

Figure 8. Average flexural properties as a function of reinforcement methods: (**a**) flexural strength and (**b**) flexural modulus.

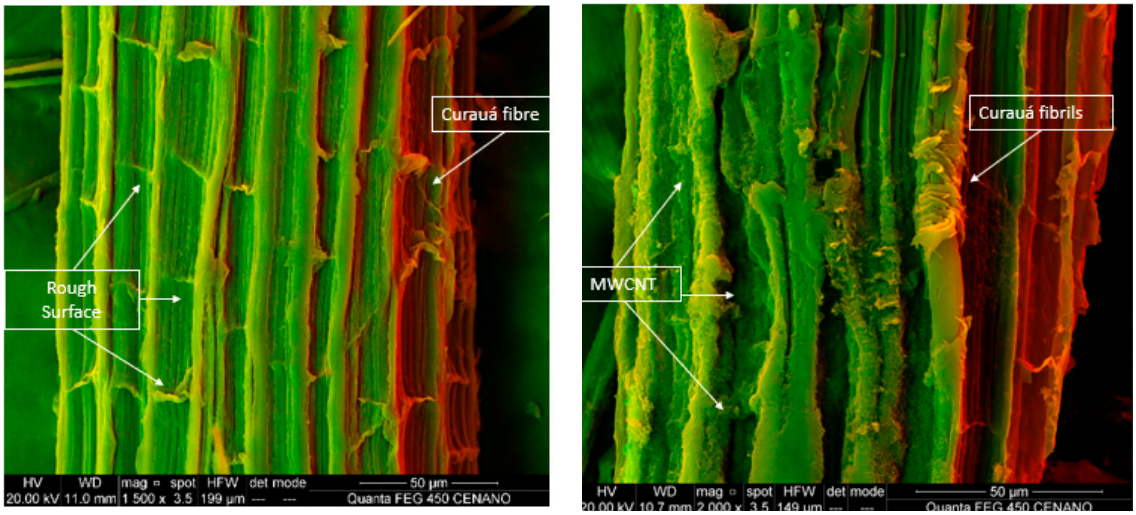
The addition of MWCNTs to the fibers and matrices of the composites affected the flexural properties of the composites. Both the curauá + (resin + MWCNT) and (curauá + MWCNT) + resin composites presented higher stiffness values when compared to the unmodified curauá fiber reinforced composite. The curauá + (resin + MWCNT) composite specimens showed an increase of approx. 67% in flexural strength, while the (curauá + MWCNT) + resin composite specimens indicated an increase of approx. 105% when compared to the unmodified curauá composite. The existing literature supports the concept that introducing fillers into the matrix reduces the formation of voids typically observed at the fiber–matrix interface, consequently enhancing the efficient transfer of loads between the reinforcement and the matrix.

Similar to its impact on flexural strength, the addition of MWCNTs also had an effect on the flexural modulus (see Figure 8b). The flexural modulus of the curauá + (resin + MWCNT) composite increased by approx. 42%, while for the (curauá + MWCNT) + resin composite, it increased by approx. 116%. The literature demonstrates that integrating fillers into the matrix effectively mitigates void formation between the fiber–matrix interface, thereby enhancing the load transfer efficiency between the reinforcement and the matrix [11]. The presence of nanoparticles delays the onset of cracking in a polymer in addition to increasing a composite's flexural strength [36].

To summarize, the mechanical properties of natural-fiber-reinforced polymer composites modified with MWCNTs are greatly influenced by the interactions between the nanofillers and the polymer matrix.

4. SEM Analysis

In order to investigate the effect of the filler reinforcement on the morphology of the fibers, an SEM analysis was performed on the single fibers. Figure 9 presents the representative SEM images of the curauá fiber morphology for both the neat and modified cases (see Figure 9a,b). The curauá fibers present a rough yet star-shaped (when viewed cross-sectionally (see Figure 9a)) geometry, where deep grooves are separated by fiber surface protrusions (microfibrils). This is responsible for the significant mechanical interlocking between the fiber and the matrix [28] (see Figure 10); the opposite is observed for natural fibers with smooth surfaces such as jute [37]. Patches of MWCNT agglomerations are visible, and this is due to the high tendency of nano-scale fillers to clump together [38]; however, they tend to be within the grooves, potentially adding to the already significant degree of mechanical interlocking of the fiber/resin interface. This can be clearly seen in Figure 10, where the partial pull-out of a coated curauá fiber is visible in the SEM image of the failure surface. The curauá fiber cross-section morphology imprint is visible on the resin matrix failure surface in addition to a part of the fiber that was left bonded, indicating good adhesion. The side of the fiber with superior adhesion likely had more MWCNTs deposited within the grooves. These observations are in agreement with the general mechanical properties found in this research, where the MWCNT-modified curauá specimens presented the most promising results.



(**a**) (**b**)

Figure 9. Representative SEM images of the fiber morphology: (**a**) curauá fiber and (**b**) MWCNT-modified curauá fiber.

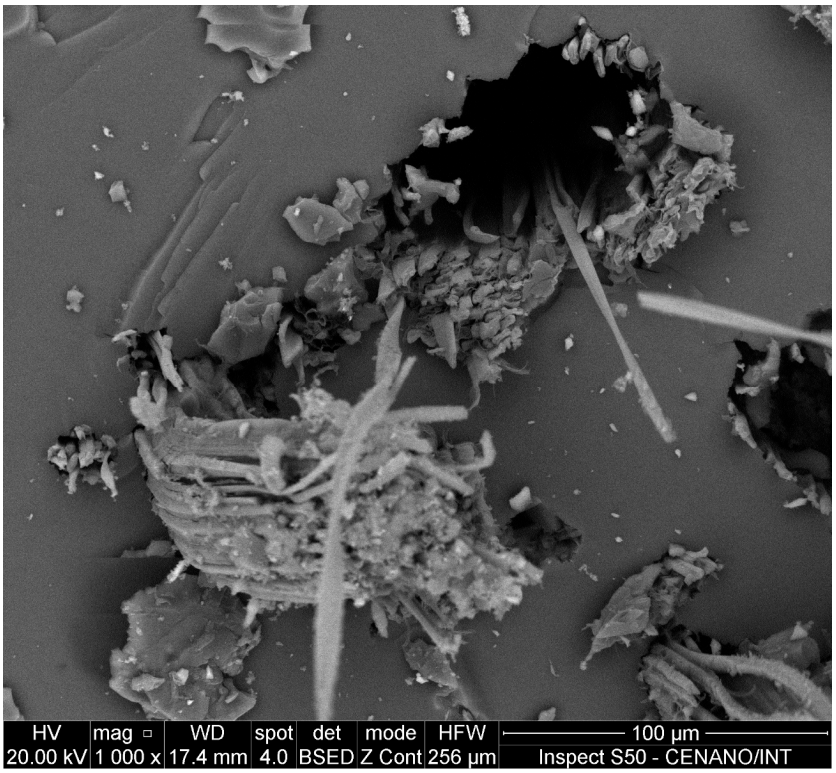


Figure 10. Representative MWCNT-modified curauá composite fiber failure.

5. Conclusions

In this work, the effect of the addition of MWCNTs on the mechanical and thermal properties of curauá-fiber-reinforced composites was investigated. MWCNT-coated curauá fibers were fabricated, and fiber-reinforced composites were developed using two different methods of filler reinforcement. These methods include the direct coating of MWCNTs onto the fibers and incorporating MWCNTs into the resin matrix prior to composite fabrication. The following conclusions were drawn.

The incorporation of the nanoparticles into the curauá fiber had a positive effect on its tensile properties (the MWCNT-modified curauá fiber presented an increase in tensile strength of approx. 26% and Young's modulus of approx. 21% when compared to unmodified curauá fiber).

The mechanical performance of curauá fiber composites was also improved by the addition of the MWCNTs onto the fibers or into the resin matrix. The tensile and flexural properties of the curauá + (resin + MWCNT) and (curauá + MWCNT) + resin composites increased when compared with those of the unmodified curauá composite specimens. The enhancement in the mechanical properties of the MWCNT-modified curauá fiber composites was attributed to improved and strong interfacial interaction between the MWCNTs and the curauá fiber.

The addition of MWCNTs in natural fibers and composites improved their thermal properties. The T_{IDT} e T_{FDT} increased with the presence of MWCNTs when compared to the pure natural fiber specimens. The T_{DTG} values also demonstrate that the MWCNTs provoked an improvement in the thermal stability of the natural fiber and composites.

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