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Effect of plant short fibers on the mechanical properties of carbon fiber reinforced epoxy matrix by using FEM based numerical homogenization technique

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ABSTRACT

In this study, we utilized the material design library in Ansys Product 2022 R1 to analyze the impact of short plant fibers on the mechanical properties of epoxy resin. We employed the representative volume element (RVE) approach and examined different volume fractions up to 50%. The technique employed in this study was multi-scale modeling based on the finite element method (FEM) for numerical homogenization. Subsequently, we used the same software to develop a five-layer laminated composite. The samples were based on epoxy resin enriched with short plant fibers at fractions of 20% and 30%, as well as pure epoxy resin. The laminated composites were reinforced with carbon fibers. The objective of this study was to analyze the mechanical response of each sample during a tensile test, focusing on multiple parameters. The sought-after results included total deformation, directional deformation, equivalent and elastic stress (Von-mises). The samples containing epoxy resin enriched with 30% of short hemp fibers exhibited remarkable mechanical strength compared to the other samples. These results suggest that the incorporation of short hemp fibers into the matrix led to a significant improvement in the mechanical strength of the composite.

Keywords: *Plant short fiber, Finite element method, Numerical homogenization technique, Carbon fibers, Epoxy matrix, Composite laminate.*

1. Introduction

The field of reinforced polymer research has been growing steadily over the past decades, and remains attractive because of its potential to combine performance and production costs at the industry level. The ever-increasing consumer demand is driving the development of new generations of multiphase polymeric products. This result in an increasing quantity of complex products in the recovery centers, and most of the time, these products end up in landfills or are incinerated or depolymerized for energy and chemical conversion. We understand the societal concern to recycle these products in order to reduce the environmental impact [1-4,14]

Composites reinforced with short fibers have the advantage of being easy to manufacture and of exhibiting good mechanical properties. Because the short fibers are easily mixed with the liquid matrix resin and the mixture can be injection or compression molded to produce components with complicated shapes, composites composed of spatially distributed particles have become popular in a wide variety of applications industrial. Additionally, using these spatially distributed short fibers and particles as they reinforce polymers in a controlled manner can provide more balanced properties, leading to improved particle-reinforced composites. In order to obtain realistic predictions of the macroscopic behavior of a new material by computational means, three-dimensional numerical simulations of statistically representative materials are necessary. Digital three-dimensional statistically representative micro-heterogeneous samples are unavoidable.

There are several methods to improve the mechanical properties of polymers. The addition of long fibers, shorts fibers, nanoparticles or microparticles, randomly or orderly, such as glass or carbon fibers, and also natural fibers, such as hemp fibers, banana fibers, jute fibers, and kenaf fibers. On the other hand, reinforcements can be used in many forms, especially long fibers [5]. Another method is the addition of silicon carbide (SiC) particles to the epoxy resin in order to increase its mechanical properties [6]. The addition of solid particle erosion to the glass fiber reinforced epoxy composite is used to improve the mechanical properties of polymers [7]. Composite material is reinforced with randomly distributed spherical particles in order to evaluate the effective material properties [8]. Another technique is to use reinforcement in powder form in order to increase the mechanical properties of polymers [9-12].

Carbon fibers have been selected because of their resistance and rigidity. They have been combined with a resinous matrix (epoxy or polyester) which allows an easy shaping. We have thus obtained a composite material which has dual characteristics; the resin and fiber components have mechanical properties almost at the extremes of the material range. The composite in the form of folds arranged according to the directions of loading constitutes a stratified composite. The judicious orientation of the folds makes it possible to match, and thus optimize the load axes and the axes of rigidity of the structure. Currently, this material can no longer be described as "new". Moreover, its field of application has largely opened to more "popular" fields: sports (tennis, cycling, skiing), automobile [13-18], wind energy [19-20], aerospace [21-23], railway [24-25], nautical [26-27], civil engineering [28-30], biomechanical industries [31-36].

Besides the carbon fibers, other reinforcing materials such as glass fibers are also used. However, their mechanical properties remain lower compared to the carbon fibers properties due to the high linkage between the carbon atoms [33].

In comparison to metals, the utilization of carbon fiber reinforced polymers for various automobile components offers the benefit of reduced weight. However, using plastic material in its original state as a resin leads to a lower mechanical strength. The objective of this study is to improve the mechanical properties of the epoxy resins by adding short vegetable fibers (hemp fiber and jute fiber) because of their good mechanical and chemical properties.

Multiscale modeling is the field of solving problems that have important features on multiple temporal and/or spatial scales. Multiple models with different resolution scales to describe the system are used. Multiscale modeling can be applied in different fields, such as composite materials, which can cover all length scales from atoms to engineered structures. In this manuscript, we have developed a multi-scale approach to study the effect of short natural fibers used on the mechanical properties epoxy resin before being used as matrix in a laminated composite reinforced by carbon fibers.

2. MATERIALS AND METHOD

2.1 Materials

Matrix: Resin-epoxy was selected from ANSYS 2022 R1 Table 1 shows its mechanical properties. Plant fibers used in this study are: Hemp fibers, and Jute fibers. Table 2 shows the mechanical properties of the natural fibers used.

Reinforcement: Carbon fibers were selected from the ANSYS library and used as reinforcement to lay up composite laminates. Table 3 shows the mechanical properties of the carbon fibers used.

Resin-epoxy was prepared before being used by adding different volume fractions of hemp and jute fibers in order to improve its mechanical properties. The resin-epoxy was enriched by 10%, 20%, 30%, 40% and 50% of vegetable short fiber. The effective elastic properties of the enriched resin-epoxy are given in the Tables 5 and 6.

Table 1 Mechanical properties of non-enriched resin-epoxy

ρ (kg m^{-3})	E (GPa)	G (GPa)	K (GPa)	σ_y (GPa)	ν
1160	3.78	1.50×10^9	4.20×10^9	0.0546	0.35

ρ: Density, **E:** Young's Modulus, **G:** Shear Modulus, **K:** Bulk Modulus, σ_y**:** Tensile Yield Strength, υ: Poisson's Ratio,

Table 2 Mechanical properties of the used plant fibers [37]

	ρ (kg m^{-3})	E (Pa)	G (Pa)	K (Pa)	σ (Pa)	ν
Hemp fibers	1480	7.00×10^{10}	2.61×10^{10}	7.29×10^{10}	6.50×10^{10}	0.34
Jute fibers	1450	4.38×10^{10}	1.65×10^{10}	4.05×10^{10}	5.50×10^{10}	0.32

Table 3 Mechanical properties of the used carbon fibers

ρ (kg □$^{-3}$)	**Ex (GPa)**	**Ey=Ez (GPa)**	**Gyz (MPa)**	**Gxy=Gxz (MPa)**	**νxy=νxz**	**νyz**
1800	395	6	2.14	8	0.2	0.2

2.2 METHOD

Preparation of the resin: The resin-epoxy is prepared in the library “MATERIALSDESIGNER” in Ansys Product 2022 R1. The used resin is the resin-epoxy selected from Ansys library. Then, a new library was created in Ansys to define hemp and jute fibers. The resin-epoxy is randomly enriched by plant short fibers at different volume fractions, 10%, 20%, 30%, 40%, and 50%. A multi-scale scheme (see Figure 1) was developed to study the effective elastic properties as a function of the volume fraction of plant short fibers reinforced resin-epoxy.

In the end, the non-enriched resin-epoxy, the resin-epoxy enriched with 20% and the resin-epoxy enriched with 30% of plant short fibers will be used to construct a stratified composite material reinforced by carbon fibers.

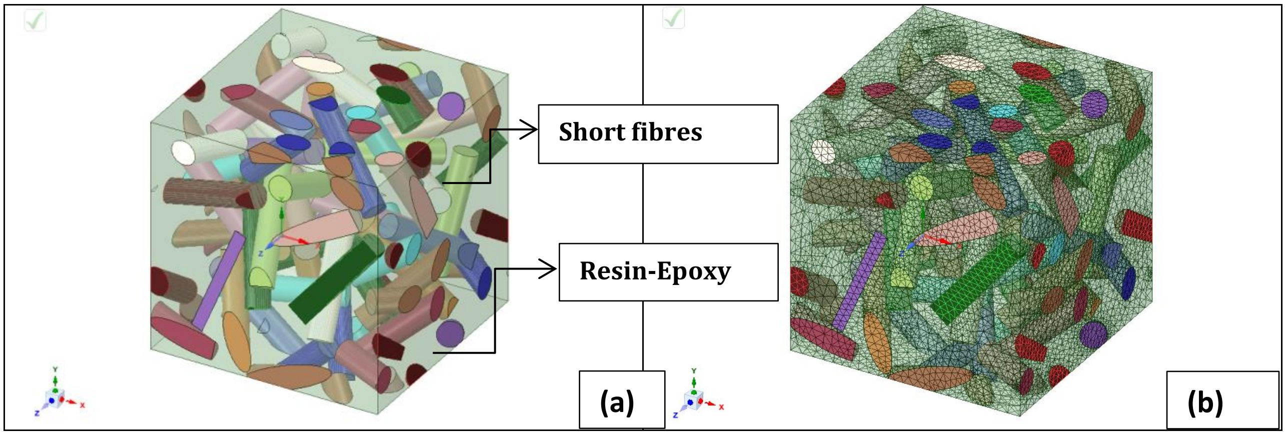

Figure 1. Representative volume element (RVE) models of composites reinforced with randomly distributed plant short fiber. (a): RVE represents short fibers and epoxy resin, (b): Meshed RVE.

Preparation of the composite laminate: The design of the geometry is done on the "DesignModeler" library on Ansys workbench. The composite laminate is made up of 5 layers. The first layer contains resin-epoxy, the second layer contains carbon fibers, the third layer contains resin-epoxy, the fourth layer contains carbon fibers, and the fifth layer contains resin-epoxy. The details of these layers are given in Figure 2.

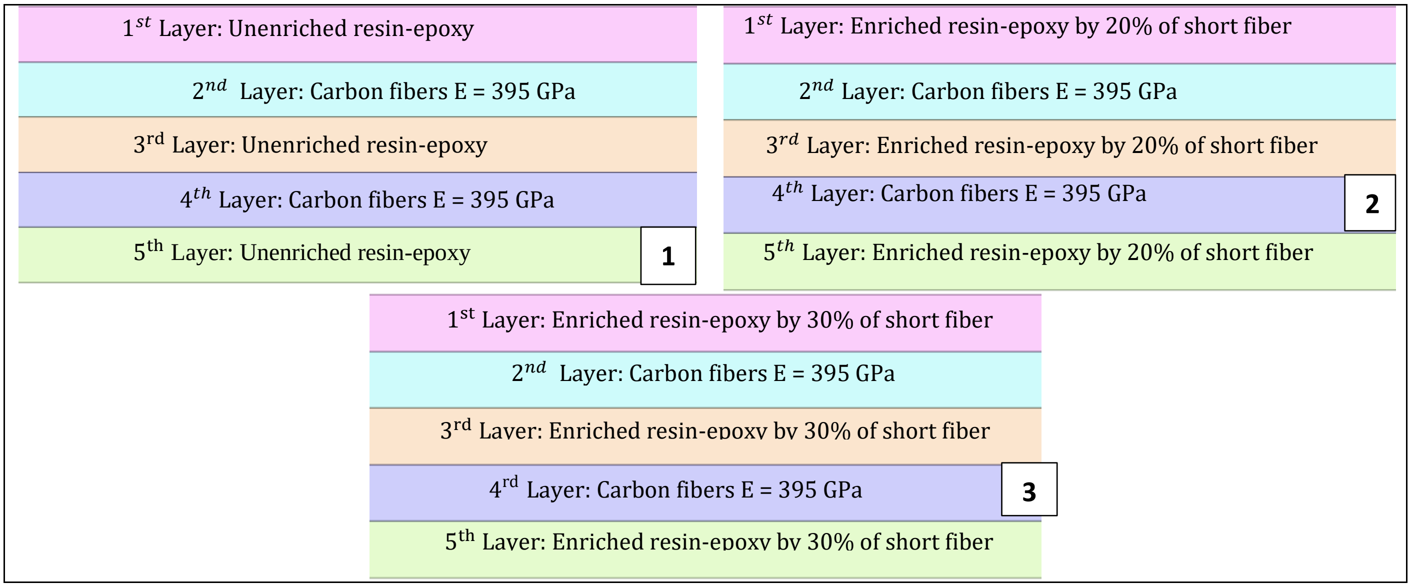

Figure 2. Description of different samples. Sample 1: based on no-enriched resin-epoxy. Sample 2: based on resin-epoxy enriched by 20% of plant short fibers. Sample 3: based on resin-epoxy enriched by 30% of plant short fibers reinforced by carbon fibers.

Table 4 Geometry of laminated composite (macro scale)

Thickness [cm]	2.5
Length [cm]	50
With [cm]	35
Volume [cm^3]	4375

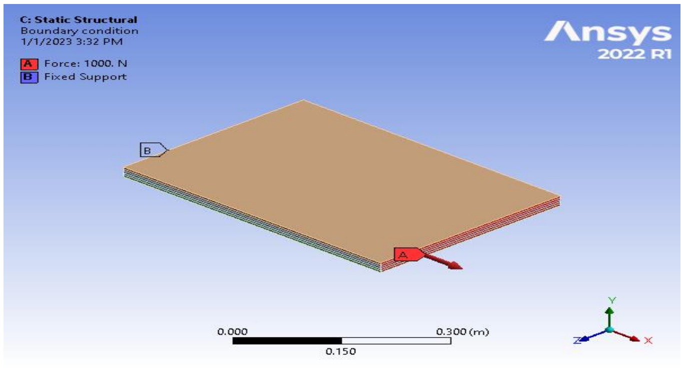

Figure 3. Boundary conditions of tensile test

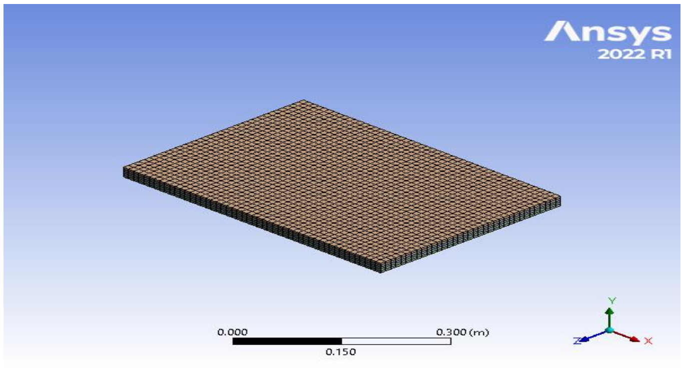

Figure 4. Model meshed

The tensile test is performed in the "Static structural" library on Ansys workbench. In order to apply the tensile force, one side was fixed, and the forces are applied on the opposite side along the X-direction (direction of carbon fibers), for several forces ranging from 1 kN to 4 kN (see Figure 3)

The meshing (Figure 4) of structural models in Ansys Mechanical is about balancing accuracy against computational expense. In general, finer meshes with smaller elements produce more accurate results. However, finer meshes take longer to solve. The meshing size used in this study is 10^{-2} m. The structure's mesh, created to ensure a gradual evolution of stress solutions with respect to its size [38], comprises 8750 elements and 63390 nodes.

The proposed approach has the following significant features using ANSYS product 2022 r1:

- Extracting the Young's modulus and the Shear modulus of the epoxy resin enriched by hemp and jute short fibers using multistate technique.
- Preparation of the geometry of a composite laminate consisting of five layers.
- Apply tensile force in X-direction (direction of carbon fiber) on several samples, whereby the first sample is based on pure epoxy resin reinforced by carbon fiber, the second sample is based on epoxy resin enriched with 20% of short fibers reinforced by carbon fiber, and the third sample is based on epoxy resin enriched with 30% of short plant fibers reinforced by carbon fiber. The results sought are, total deformation, directional deformation, equivalent stress and equivalent strain.

3. Results

Tables 5 and 6 show the effective elastic properties measured on epoxy matrix composites enriched with hemp and jute short fibers. The variation of the volume fraction of short fibers is the same for each sample which are: 10%, 20%, 30%, 40% and 50%. These tables allow us to trace the variation of the effective elastic properties according to the volume fraction of short fibers (Figure 5, to Figure10)

In this paragraph we will compare the variation of Young's moduli (E_{11}, E_{22} and, E_{33}), and Shear moduli (G_{12}, G_{23} and, G_{31}), according to the variation of volume fraction of the plant short fibers of different samples.

According to the results obtained, it is remarkable that the Young's moduli (E_{11}, E_{22} and, E_{33}), and the Shear modulii (G_{12}, G_{23} and; G_{31}) increase in proportion to the increase in the volume fraction of the short plant fibers up to 50%. Once the volume fraction rate surpasses 30%, there is a notable deceleration in the augmentation of Young's and Shear moduli. In other words, the composite begins to deviate from its homogenous mixing behavior, leading to a reduction in the mechanical properties of plant short fibers, as evidenced by Figure 5 to Figure 10 and Table 5, Table 6.

Note that the resin-epoxy enriched with hemp short fiber showed higher Young's moduli and high Shear moduli than the jute short fiber reinforced epoxy resin.

The addition of plant short fibers in the epoxy resin should not exceed 30% in order not to lose the mechanical and chemical characteristics of the matrix (epoxy resin) that can maintain good adhesion between the reinforcement (natural fibers used) and the epoxy resin.

To maintain good adhesion between the reinforcement (natural fibers used) and the matrix (epoxy resin), it is necessary to add reasonable quantities of reinforcement to the matrix, otherwise adhesion will be poor, which will have a negative impact on the mechanical strength of the composite.

Table 5 Variation of the effective elastic properties at different volume fraction of hemp short fibers

Fiber volume fraction (%)	10	20	30	40	50
E_11 (MPa)	4871.5	6188.1	6491.5	6490.1	6802.7
E_22 (MPa)	4883.4	6374.3	6242.0	6197.2	6642.8
E_33 (MPa)	4914.8	6256.1	6422.6	6594.0	6789.4
G_11 (MPa)	1817.2	2326.7	2329.0	2315.2	2477.6
G_22 (MPa)	1807.9	2334.1	2328.9	2377.9	2379.5
G_33 (MPa)	1817.7	2305.9	2346.5	2252.2	2405.2

Table 6 Variation of the elastic orthotropic properties at different volume fraction of jute short fibers

Fiber volume fraction (%)	10	20	30	40	50

E_11 (MPa)	4713.1	5852.3	6206.2	6395.9	6524.8
E_22 (MPa)	4794.8	5951.3	6088.4	6113.0	6284.5
E_33 (MPa)	4754.2	5967.3	6192.2	6165.7	6341.0
G_12 (MPa)	1745.3	2167.9	2321.8	2321.6	2396.4
G_23 (MPa)	1741.3	2161.6	2239.0	2252.6	2308.8
G_31 (MPa)	1759.5	2203.9	2281.0	2311.3	2447.4

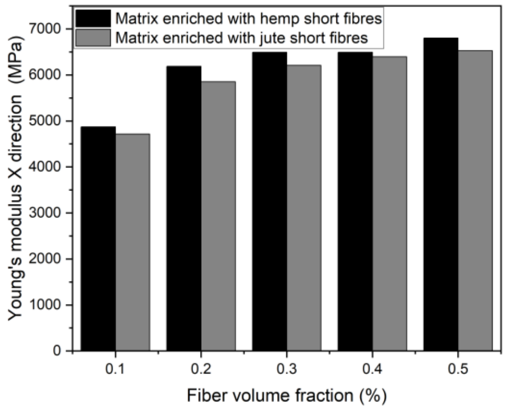

Figure 5. Young's Modulus X direction (E_{11})

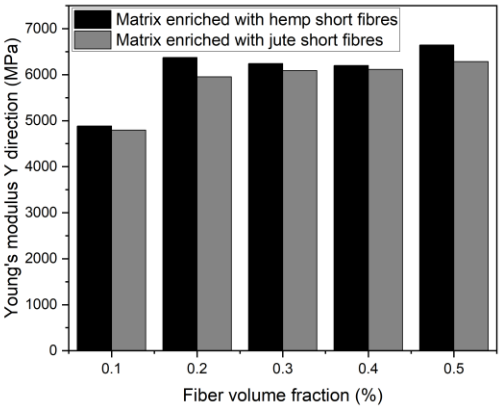

Figure 6. Young's Modulus Y direction (E_{22})

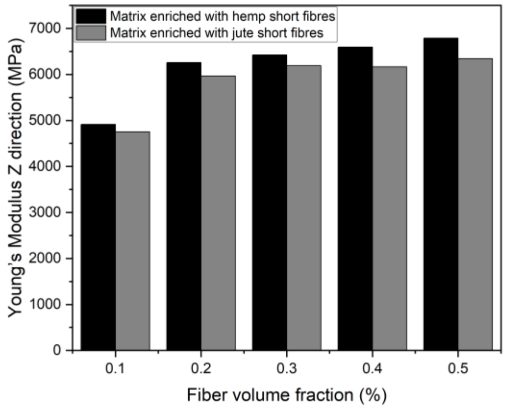

Figure 7. Young's Modulus Z direction (E_{33})

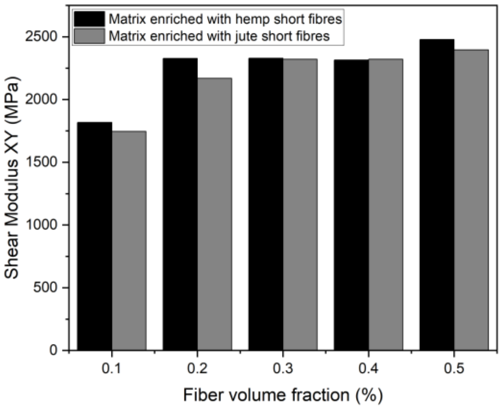

Figure 8. Shear Modulus XY direction (G_{21})

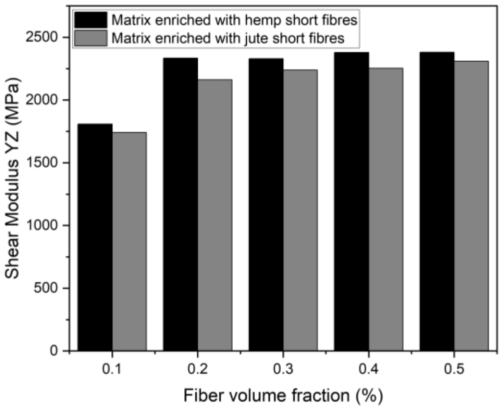

Figure 9. Shear Modulus YZ direction ($\boldsymbol{G_{23}}$)

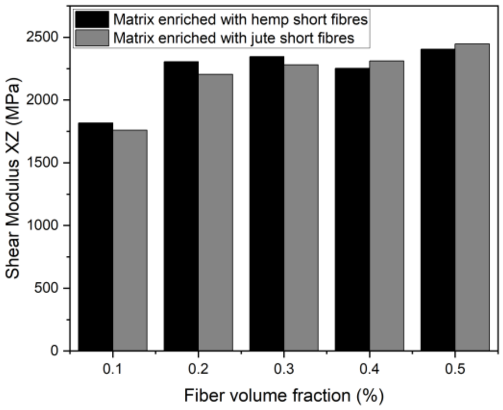

Figure 10. Shear Modulus XZ direction ($\boldsymbol{G_{31}}$)

4. Response of the samples to the tensile test in X-direction (direction of carbon fiber)

In the following, we will apply the tensile test (Figure 4) to different samples. The first sample is based on non-enriched resin-epoxy reinforced by carbon fibers. The second sample is based on resin-epoxy enriched by 20% by plant short fibers used reinforced with carbon fibers. The third sample is based on resin-epoxy enriched by 30% of plant short fibers used reinforced with carbon fibers.

4.1 Sample based on no-enriched resin epoxy reinforced by carbon fiber

The composite sample made of resin epoxy reinforced with carbon fiber was analyzed and it was discovered that both the total deformation and directional deformation were at a minimum value of 0 mm and maximal value at 2.8595×10^{-3} mm, and 2.6971×10^{-3} mm, respectively under a tensile force F = 4000N, as shown in Figure 11(a), Figure 11(b) and Table 7.

The equivalent stress has a maximum value of 1.72 MPa and the equivalent strain has a maximum value of 1.6823×10^{-4} mm/mm. The details are posted on Figure 11(c), Figure 11(d) and Table 7.

Table 7 Maximal total deformation, maximal directional deformation, equivalent elastic stress (Von-Mises) and Equivalent elastic strain (Von-Mises) of composite laminate based on no-enriched resin-epoxy reinforced by carbon fibers.

	Total deformation [mm]	**Directional deformation [mm]**	**Equivalent elastic stress (Von-Mises) [MPa]**	**Equivalent elastic strain (Von-Mises) [mm/mm]**
VF[%]	0	0	0	0
1000 N	7.1488×10^{-4}	6.7428×10^{-4}	0.43001	4.2057×10^{-5}
2000 N	1.4298×10^{-3}	1.3486×10^{-3}	0.86002	8.4113×10^{-5}
3000 N	2.1446×10^{-3}	2.0229×10^{-3}	1.29000	1.2617×10^{-4}
4000 N	2.8595×10^{-3}	2.6971×10^{-3}	1.72000	1.6823×10^{-4}

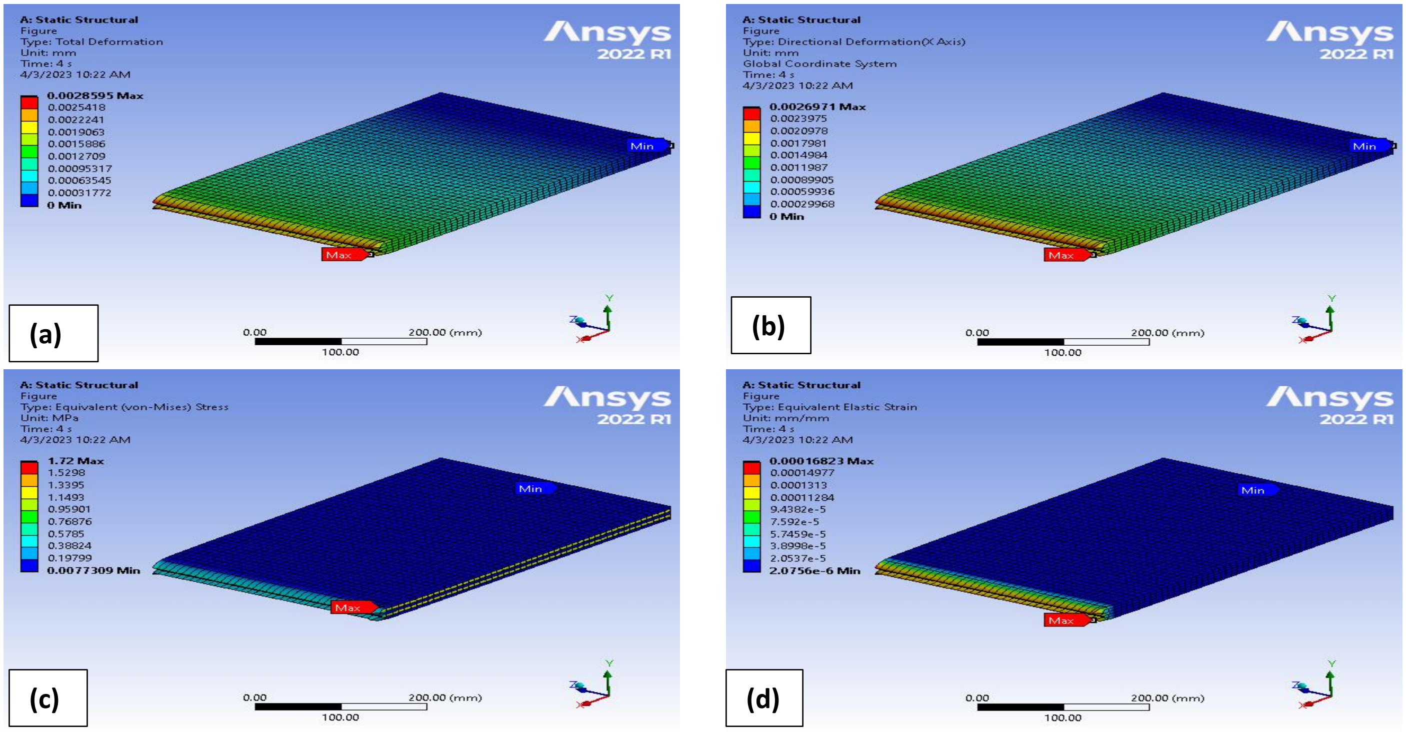

Figure 11. Sample based on non-enriched resin-epoxy reinforced by carbon fibers, (a) Total deformation (b) Directional deformation (c) Equivalent Stress (d) Equivalent Strain

4.2 Sample based on enriched resin epoxy by 20% and 30% of hemp short fiber reinforced with carbon fiber

The total static structural deformation and directional deformation of the composite based on enriched resin epoxy by 20% of hemp short fiber reinforced with carbon fiber were found to have a minimum value of 0 mm, and a maximum value of 2.3438×10^{-3} mm , and 2.2425×10^{-3} mm, respectively, which has been shown in Figure 12(a), Figure 12(b) and Table 8. The equivalent stress has a maximum value of 1.57290 MPa and the equivalent strain has a maximum value of 1.0243×10^{-4}mm/mm . The details are shown in Figure 12(c), Figure 12(d) and Table 9.

Table 8 Maximal total deformation and maximal directional deformation of composite laminate based on resin-epoxy enriched by 20% and 30% of hemp short fibers reinforced by carbon fibers.

	Total deformation [mm]		Directional deformation [mm]	
VF[%]	20	30	20	30
1000 N	5.8595×10^{-4}	5.7853×10^{-4}	5.6063×10^{-4}	5.5388×10^{-4}
2000 N	1.1719×10^{-3}	1.1571×10^{-3}	1.1213×10^{-3}	1.1078×10^{-3}
3000 N	1.7578×10^{-3}	1.7356×10^{-3}	1.6819×10^{-3}	1.6616×10^{-3}
4000 N	2.3438×10^{-3}	2.3141×10^{-3}	2.2425×10^{-3}	2.2155×10^{-3}

Table 9 Maximal equivalent elastic stress and maximal equivalent elastic strain of composite laminate based on resin-epoxy enriched by 20% and 30% of hemp short fibers reinforced by carbon fibers.

	Equivalent elastic stress (Von-Mises) [MPa]		**Equivalent elastic strain(Von-Mises) [mm/mm]**	
VF[%]	20	30	20	30
1000 N	0.39322	0.38795	2.56080×10^{-5}	2.4725×10^{-5}
2000 N	0.78645	0.7759	$5.1216E \times 10^{-5}$	4.9450×10^{-5}
3000 N	1.17970	1.1639	7.68240×10^{-5}	7.4176×10^{-5}
4000 N	1.57290	1.5518	1.02430×10^{-4}	9.8901×10^{-5}

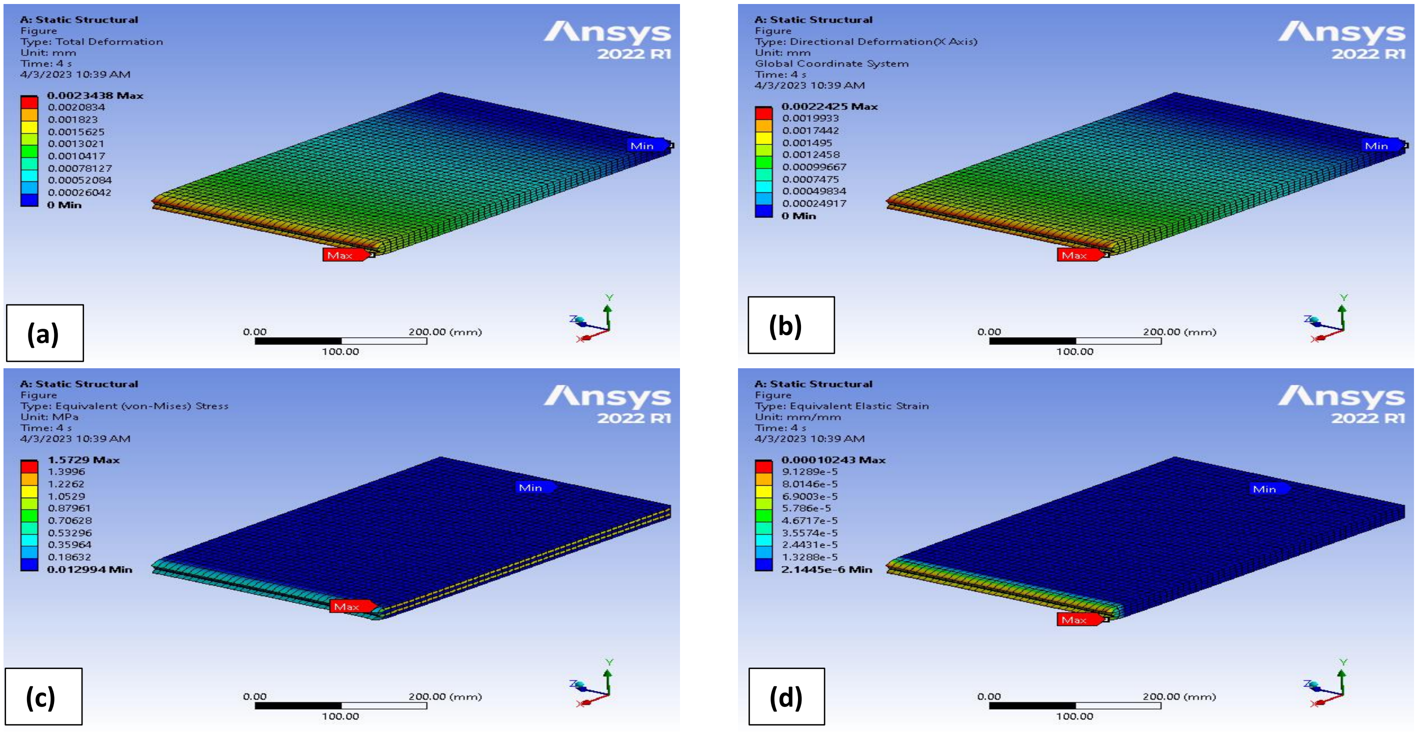

Figure 12. Sample based on resin-epoxy enriched by 20% of hemp short fiber, (a) Total deformation (b) Directional deformation (c) Equivalent Stress (d) Equivalent Elastic Strain

Static structural total deformation and direction deformation of sample based on resin epoxy enriched by 30% of hemp short fiber reinforced with carbon fiber are found to have minimum value of 0 mm, and a maximum value of 2.3141×10^{-3} mm, and 2.2155×10^{-3} mm respectively, as shown in Figure 13(a), Figure 13(b) and Table 8. The maximal value of static structural equivalent stress and equivalent strain are: 1.5518 MPa, 9.8901×10^{-5} mm/mm, respectively as Figure 13(c) and Figure 13(d) and Table 9 showed.

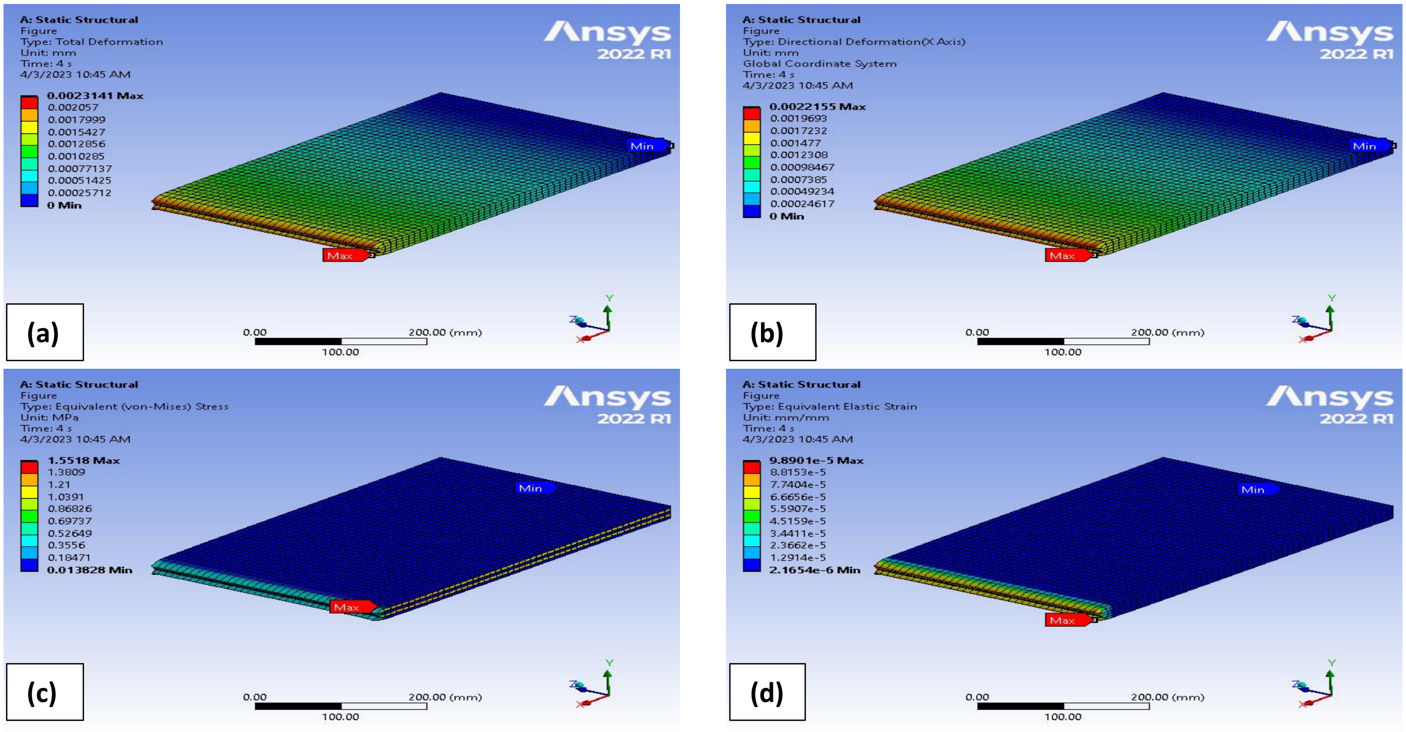

Figure 13. Sample based on resin-epoxy enriched with 30% of hemp short fiber, (a) Total deformation (b) Directional deformation (c) Equivalent Stress (d) Equivalent Elastic Strain

4.2 Sample based on enriched resin epoxy by 20% and 30% of jute short fiber reinforced by carbon fiber

Static structural total deformation and directional deformation of laminated composite based on resin epoxy enriched by 20% jute short fibers reinforced by carbon fiber were found to have a minimum value 0 mm, and maximum value of 2.3919×10^{-3}mm, and 2.2866×10^{-3} mm, respectively. The detail is given on Figure 14(a), Figure 14(b) and Table 10. The maximal value of static structural equivalent stress and equivalent strain are: $1.58870\ \mathrm{MPa}$, $1.0841 \times 10^{-5}\ \mathrm{mm/mm}$. [see Figure 14(c), Figure 14(d) and Table 11].

Table 10 Maximal total deformation and maximal directional deformation of composite laminate based on resin-epoxy enriched by 20% and 30% of jute fibers reinforced by carbon fibers

	Total deformation [mm]		**Directional deformation [mm]**	
VF[%]	20	30	20	30
1000 N	5.9798×10^{-4}	5.8552×10^{-4}	5.7164×10^{-4}	5.6045×10^{-4}
2000 N	1.1960×10^{-3}	1.1710×10^{-3}	1.1433×10^{-3}	1.1209×10^{-3}
3000 N	1.7939×10^{-3}	1.7566×10^{-3}	1.7149×10^{-3}	1.6814×10^{-3}
4000 N	2.3919×10^{-3}	2.3421×10^{-3}	2.2866×10^{-3}	2.2418×10^{-3}

Table 11 Maximal equivalent elastic stress and maximal equivalent elastic strain of composite laminate based on unenriched resin-epoxy, resin-epoxy enriched by 20% and 30% of jute fibers reinforced by carbon fibers.

	Equivalent elastic stress (Von-Mises) [MPa]		**Equivalent elastic strain (Von-Mises) [mm/mm]**	
VF[%]	20	30	20	30
1000 N	0.39717	0.39291	2.7103×10^{-5}	2.5596×10^{-5}
2000 N	0.79435	0.78581	5.4205×10^{-5}	5.1192×10^{-5}
3000 N	1.19150	1.17870	8.1308×10^{-5}	7.6788×10^{-5}
4000 N	1.58870	1.57160	1.0841×10^{-4}	1.0238×10^{-4}

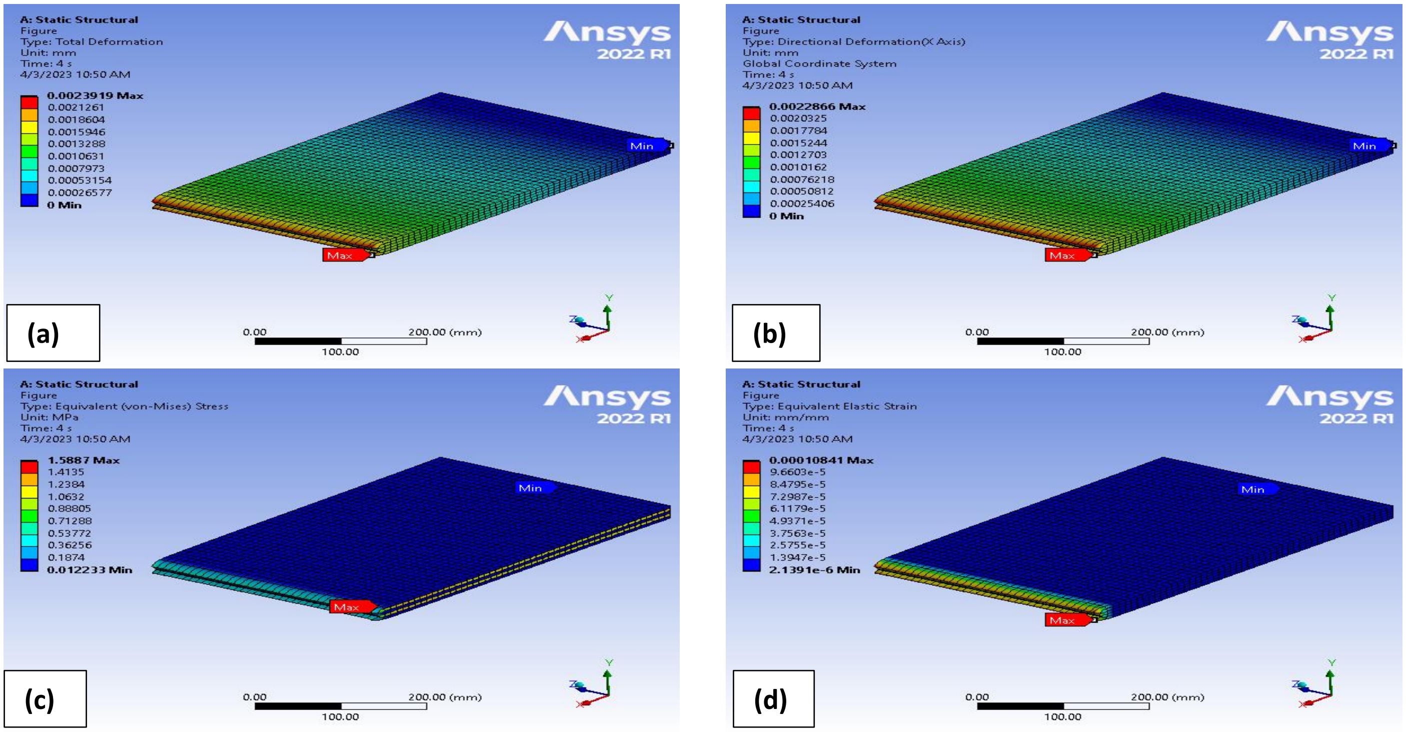

Figure 14. Sample based on resin-epoxy enriched with 20% of jute short fiber, (a) Total deformation (b) Directional deformation (c) Equivalent Stress (d) Equivalent Strain

The maximal total deformation and maximal directional deformation of laminated composite based on resin epoxy enriched by 30% of jute short fibers reinforced by carbon fibers are: $\mathbf{2.3421 \times 10^{-3}\ mm}$, and $\mathbf{2.2418 \times 10^{-3}\ mm}$ respectively, the details are given on Figure 15(a), Figure 15(b) and Table 10. In the other hand the maximal value of equivalent stress is: $\mathbf{1.57260\ MPa}$ and maximal value of equivalent strain is: $\mathbf{1.0238 \times 10^{-4}\ mm/mm}$, see the details on Figure 15(c), Figure 15(d) and Table 11.

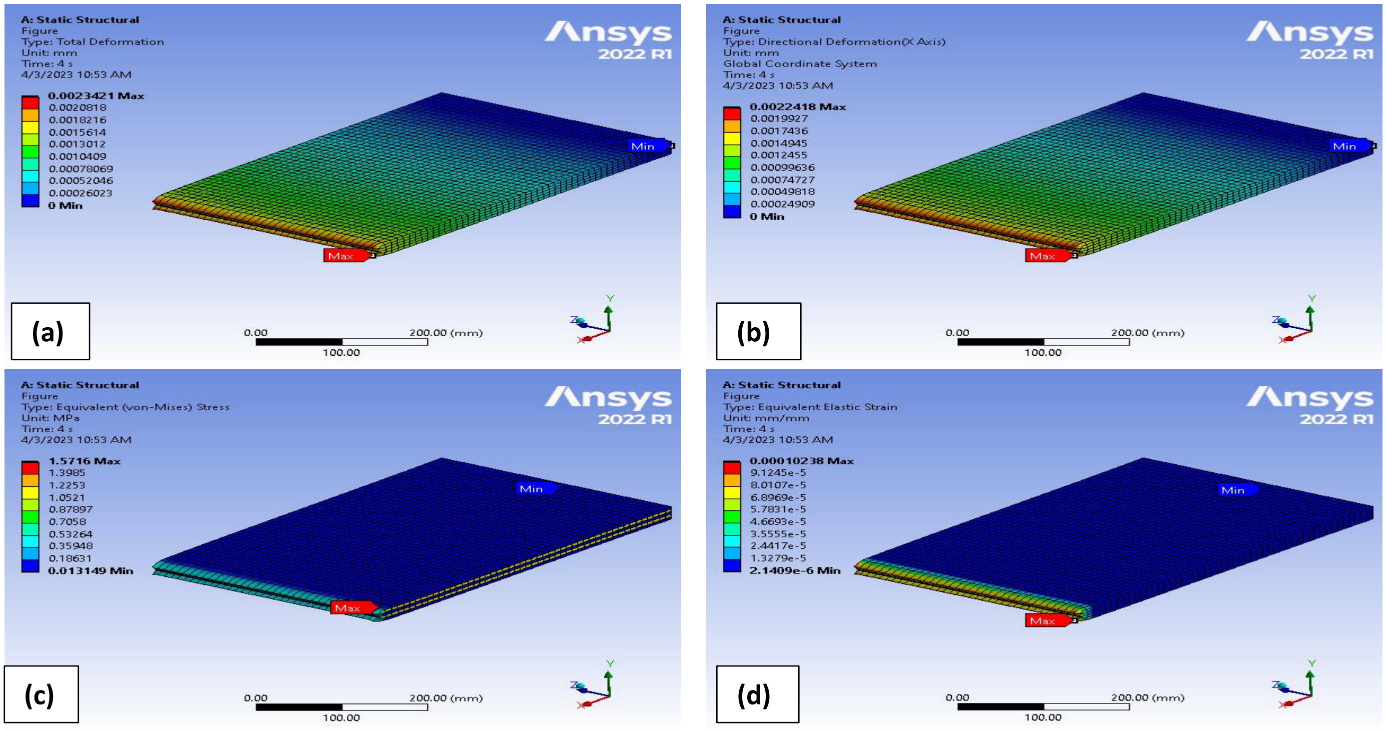

Figure 15. Sample based on resin-epoxy enriched with 30% of jute short fiber, (a) Total deformation (b) Directional deformation (c) Equivalent Stress (d) Equivalent Elastic Strain

The laminated composite based on resin-epoxy enriched by hemp fibers reinforced by carbon fibers showed less maximal total deformation, less directional deformation against several tensile forces applied range 1000 N to 4000 N compared to the other samples, the same samples are showed less maximal equivalent strain and less equivalent stress, this means the samples based on resin-epoxy enriched by hemp short fiber have a higher mechanical resistance compared to the other samples based on epoxy resin enriched by jute fibers, and the sample based on pure epoxy resin.

5. Conclusion

The effect of short fiber reinforcements on the mechanical strength of stratified composites against tensile test is noticeable; the use of pure resin-epoxy (non-enriched resin-epoxy by plant short fibers) in a composite laminate shows less mechanical strength than resin-epoxy enriched with plant reinforcements. The laminated composite that has shown the highest strength is based on resin-epoxy enriched with 30% of hemp short fibers reinforced by carbon fibers.

Along with their remarkable mechanical and chemical properties, plant fibers have lower cost, are eco-friendly and less energy-demanding, for these reasons, natural fibers are recommended as reinforcements for polymer matrices. The matrix protects the fibers from environmental degradation, thus maintaining their mechanical strength. Natural fibers are less dense than synthetic fibers, are a renewable material and, in most cases, are recyclable. The motivation for using carbon fibers as reinforcements to resin-epoxy enriched with vegetable short fibers is to give much more mechanical strength to the composites. Carbon fibers offer advantages that natural products alone cannot. In addition to their remarkable mechanical properties, carbon fibers can be used as reinforcement to reduce the weight of materials which is the main goal of this kind of materials composite. This type of composite materials can be used in car bodies, such as roofs, hoods, or doors, to reduce the weight of cars in order to reduce fuel consumption.

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