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EXPERIMENTAL INVESTIGATION OF MECHANICAL PROPERTIES OF NATURAL FIBER WOVEN FABRIC COMPOSITES

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ABSTRACT

The development of polymer composites containing natural fibers as a sustainable alternative material for certain engineering applications, particularly aerospace and automotive applications, is a popular area of research. In this study, the mechanical properties of flax, jute and jute/carbon woven fabric composites were investigated and compared with those of 3K carbon woven fabric composites. The results of this study demonstrate the utility of natural fibers in composite applications. Furthermore, it is observed that the mechanical properties of natural fibres are significantly affected by changes in temperature. Experimental results prove that the mechanical properties of natural fiber composites are significantly lower than those of carbon fiber composites, but the hybridization of carbon and jute fibers can result in a composite material with enhanced mechanical properties.

Key Words: *Natural fiber composites, mechanical properties, impact properties.*

INTRODUCTION

The mechanical properties of natural fibers vary greatly with the age of the plant from which they are derived, geographical location, climatic growth conditions, the harvesting method employed, the retting and combing techniques applied, etc. [1], unlike those of synthetic fibers. The variability of these mechanical properties, the compatibility between the matrix and natural fibers and moisture absorption [2] are the principal disadvantages that may prevent the large-scale production of natural fiber composites [3]. The properties of the most widely employed natural fibers, such as flax, hemp, jute, sisal, and kenaf fibers, were studied in previous review articles at the fiber scale [4].

Owing to the adverse effects of composite materials on the environment, their high cost, and other unfavorable properties, researchers have begun to explore natural fiber-based hybrid composites. Hybrid composites, which are obtained by combining synthetic and natural fibers, have been developed to overcome the aforementioned shortcomings. Natural fibers themselves can be treated as composites, which makes them tougher than synthetic fibers; furthermore, appropriately configured high-quality natural fiber-reinforced hybrid composites possess good strength and stiffness values that approximate those of glass fiber-reinforced composites. It has been observed that the partial replacement of artificial fibers with natural fibers allows for the formation of artificial-natural hybrid composites, which show characteristics intermediate between those of purely natural and purely synthetic fiber-based composites. Indeed, researchers have demonstrated that improved properties can be achieved by hybridizing natural fiber-based composites with glass fibers.

It is clear that, despite the significant advantages of natural fibers, because of their limited mechanical properties, they are not favored for use alone in composite materials to obtain adequate reinforcement in certain applications requiring high mechanical performance [5]. In this case, hybridizing with conventional carbon and glass fibers may lead to better results [6]. Unlike those of synthetic fibers, the mechanical properties of natural fibers show a wide range of variation; therefore, it is particularly critical to determine the properties of these materials in fabric and composite structures because the properties of composite plates can also vary with the properties of yarn and fabric. Thus, the aim of this study was to investigate the mechanical properties of flax, jute and jute/carbon woven fabric composites and compare them with those of 3K carbon woven fabric composites.

MATERIALS AND METHODS

The properties and production parameters of the jute, flax, jute-carbon and carbon woven fabrics and fibers that were used in this study are presented in ***Table 1*** and ***Table 2***. The properties of the jute and flax yarn and fabrics were experimentally determined. All woven fabrics were produced under the same conditions and with the same weaving machine. The hybrid fabrics were designed to have the same yarn density as 100% carbon fabrics. In the hybrid fabrics, the warp yarns were composed of carbon, whereas the weft yarns were composed of jute. Araldit LY 564 epoxy resin and XB 3486 hardener were mixed in a weight ratio of 100:34 to produce the composite materials.

Table 1

Properties of the woven fabrics used in this study

Reinforcement Definition	Flax fabric	Jute fabric	Jute-Carbon Hybrid fabric	Carbon fabric
Reinforcement Code	R1	R2	R3	R4
Weave type	Plain woven	Plain woven	Plain woven	Plain woven
Number of threads (threads/cm)				
Weft yarn	12	7	6	6
Warp yarn	12	7	6	6
Yarn linear density (Tex)				
Weft yarn	46	230	230	200
Warp yarn	46	230	200	200
Yarn type				
Weft yarn	Ring	Ring	Ring	Filament
Warp yarn	Ring	Ring	Filament	Filament
Yarn definition and composition				
Weft yarn	100% Flax	100% Jute	100% Jute	100% Carbon
Warp yarn	100% Flax	100% Jute	100% Carbon	100% Carbon
Yarn crimp in the fabric (%)				
Weft yarn	5.8	7.7	4.2	0.1
Warp yarn	6.0	6.3	3.0	0.1
Mass per unite area (g/m^2)	120	300	150	210

Table 2

Properties of the fibers used in this study

Parameters	A-38 Carbon*	Flax [1]	Jute [1]
Fiber diameter, µm	7	15-50	40-350
Fiber Young modulus, Gpa	240	27	26.5
Fiber strength, Mpa	3800	500-1500	393-773
Fiber ultimate elongation, %	1.6	2.7-3.2	1.5-1.8
Fiber density, g/cm^3	1.78	1.53	1.3

*: *manufacturer data sheet*

Table 3

Properties of the composite plates

Sample Code	C1	C2	C3	C4
Reinforcement Type	R1	R2	R3	R4
Fabric Ply Number	12	12	12	24
Stacking direction	0°/90°	0°/90°	0°/90°	0°/90°
Plate thicknesses (mm)	4.93±0.19	10.58±0.11	8.72±0.15	6.32±0.032
Fiber Volume Fraction (%)	43	40	45	52

Composite Production

The fabrics used in the production of the composite materials were cut into 50x50 cm pieces. The end (ends/cm) and the pick count (picks/cm) of the fabrics may have differed from one another. Thus, the fabrics were slightly unbalanced with respect to the total fiber volume content in the warp and weft directions. To balance the warp- and weft-directional fibers in the composite laminate, the fabric layer orientation was alternated when laying the half-ply of samples.

Table 3 shows the main production parameters of the composite samples, such as the ply arrangement, number of fabric plies and thickness of the composite plates. The vacuum-assisted resin infusion method was used to produce the composite plates. All samples were produced on a glass plate. The samples were held under vacuum to harden for a minimum of 12 hours after resin infusion and were post-cured at 80ºC for 4 hours in an oven.

The thicknesses of the finished samples were measured using a caliper. The fiber volume fraction (V_f) was obtained based on the fabric weight and plate thickness as follows:

$$V_f = \frac{n.m}{\rho.h} \quad (1)$$

where *n* is the number of fabric plies, *m* is the areal fabric weight, *ρ* is the fiber density and *h* is the plate thickness.

The following equations were used to calculate the fiber volume fraction in the warp and weft directions separately for the hybrid composites because the warp and weft yarns were different from one another:

$$m_{warp} = \frac{\delta_{warp}}{1000} \cdot \frac{100 + \varphi_{warp}}{100} . T_{warp} \quad (2)$$

$$m_{warp} = \frac{\delta_{weft}}{1000} \cdot \frac{100 + \varphi_{weft}}{100} . T_{weft} \quad (3)$$

where m_{warp} and m_{weft} are the areal weights of the warp and fill yarns, respectively, δ is the yarn density per meter, φ is the yarn crimp percentage and T is the linear density in units of tex. The warp and weft subscripts indicate the yarns in the warp and weft directions, respectively. The fiber volume fractions in the warp and weft directions ($V_{f\text{-}warp}$ and $V_{f\text{-}weft}$) were separately identified as follows:

$$V_{f-warp} = \frac{n.m_{warp}}{\rho_{warp}.h} \quad (4)$$

$$V_{f-weft} = \frac{n.m_{weft}}{\rho_{weft}.h} \quad (5)$$

where ρ_{warp} and ρ_{weft} are the densities of the warp and weft fibers, respectively. The total fiber volume fractions ($V_{f\text{-}total}$) of the hybrid composites were obtained as follows:

$$V_{f-total} = V_{f-warp} + V_{f-weft} \quad (6)$$

Fiber volume fractions calculated for each composite sample are presented in ***Table 3***.

Tensile Properties of Composites

Tensile tests of composite samples were performed on an Instron 4505 test device with a crosshead speed of 5 mm/min in accordance with the ASTMD 3039 standard. The samples were cut into 25x250 mm pieces using a water jet, and aluminum end tabs were adhered to the ends of the samples using epoxy glue. A video extensometer was used in the tests as an optical extensometer with a precision of approximately 0.01% strain.

Impact Behavior of Composite

The impact behavior of each composite was evaluated according to (ASTM D256) at room temperature. Izod and Charpy impact tests were used to test the polymeric materials.

In these tests, the calculation of the impact strength and fracture toughness depended on the calculation of the energy required for fracture. The impact strength was calculated based on the following equation:

$$G_C = \frac{U_C}{A} \quad (7)$$

where,
Gc is the impact strength of the material (J/m^2),
Uc is the amount of absorbed energy (J), and
A is the cross-sectional area of the specimen (m^2).

Fracture toughness, which describes the ability of a material containing a crack to resist fracture can be expressed as

$$K_C = \sqrt{G_C E} \quad (8)$$

where:
Kc is the fracture toughness of the material ($MPa.m^{1/2}$) and
E is the elastic modulus of the material (Mpa).

Water Absorption Properties of Composite

The water absorption properties of samples were determined according to BS EN ISO 62. The samples were cut to dimensions of 10x10 mm. Water absorption tests were conducted by immersing the composite specimens in a deionized water bath at 25 °C until the samples nearly reached saturation. After immersion for 2 and 24 h, the specimens were taken out from the water and all surface water was removed with a clean, dry cloth; the specimens were then weighed. The percentage of water absorption in the composites was calculated by the difference in weight of the samples immersed in water and the dry samples.

RESULTS AND DISCUSSIONS

Tensile properties of composites

The results of the tensile tests are presented in Table 4, and Figure 1 a-d shows a diagram of stress vs. strain for the warp and weft directions.

Although all samples were produced under the same conditions, the yarn and fiber volume fractions of the natural fiber woven composite structures were determined to be relatively lower than those of the carbon fabric composite due to yarn construction. Gaps between the yarns in the woven structure due to the circular cross-section of the yarns led to the formation of resin-rich areas. Furthermore, the hydrophilic properties of the natural fibers caused more resin to be absorbed between the fibers in the yarns. Therefore, the fiber volume fractions of all samples were normalized to 52% to allow for meaningful comparison of tensile properties between samples. The normalization of the fiber volume fraction was exact for the UD composite along the fiber direction. For the cross-ply or woven composite, the normalization provide only an approximation, neglecting the transverse stiffness of the 90° plies.

In ***Table 4***, the values of the Young's modulus and tensile strength are also presented for all samples after being scaled to a total fiber volume fraction of 52%. Scaling the results to the same fiber volume fraction allowed for the trends to be viewed more objectively, as discussed below.

The tensile strengths of the composites in the weft direction ranked as follows, in descending order: sample C4, sample C3, sample C2 and sample C1. The tensile strengths of samples C3, C2 and C1 were 2.36, 2.56 and 4.76 times lower than the tensile strength of sample C4, respectively. The tensile strengths in the warp direction ranked as follows, in descending order: sample C4, sample C3, sample C2, and sample C1. The tensile strengths of samples C3, C2 , and C1 were 2.21 times, 2.29 times, and 4.73 times less than the tensile strength of sample C4, respectively.

Table 4

Experimentally determined tensile properties of composites

Sample	Direction	Young's Modulus (Gpa)	Young's Modulus @52% V_f (Gpa)	Tensile Strength (Mpa)	Tensile Strength @52% V_f (Mpa)	Strain at Failure (%)
C1	Warp	4.85±1.40	5.86±1.40	52.34±4.50	63.29±4.50	1.40±0.15
	Weft	5.17±1.32	6.25±1.32	53.41±6.25	64.58±6.25	1.52±0.12
C2	Warp	6.84±1.84	8.89±1.84	84.74±6.45	110.16±6.45	1.84±0.22
	Weft	7.23±1.91	9.40±1.91	80.34±5.82	104.44±5.82	1.91±0.20
C3	Warp	9.58±1.00	11.07±1.00	97.82±11.50	113.03±11.50	1.03±0.08
	Weft	9.76±1.04	11.47±1.04	95.74±8.15	110.63±8.15	1.04±0.15
C4	Warp	57.84±7.4	57.84±7.4	363.10±12.10	363.10±12.10	0.67±0.02
	Weft	56.72±2.3	56.72±2.3	372.30±15.50	372.30±15.50	0.63±0.02

The samples showed nearly identical properties in the warp and weft directions due to the stacking sequence formed during composite manufactu-ring; thus, the tensile properties in both directions were quite similar. The strength of the flax-reinforced composite was determined to be approximately 63-64 MPa for 52% V_f, which is very low compared to that of glass- or carbon-reinforced composites.

For the flax-epoxy composite, a serious non-linearity could be observed in the corresponding stress-strain curve above a certain amount of strain (***Figure 1.a***). It is believed that this behavior is related to the initiation of damage on the flax yarn. The Young's modulus of the flax-epoxy composite was approximately 6 GPa. A non-linearity was observed on the stress-strain curve above 0.5% strain, and the non-linearity increased gradually. The Young's modulus of the composite was 3.1 GPa, thereby decreasing by approximately 48% between 0.5% strain and the ultimate strain.

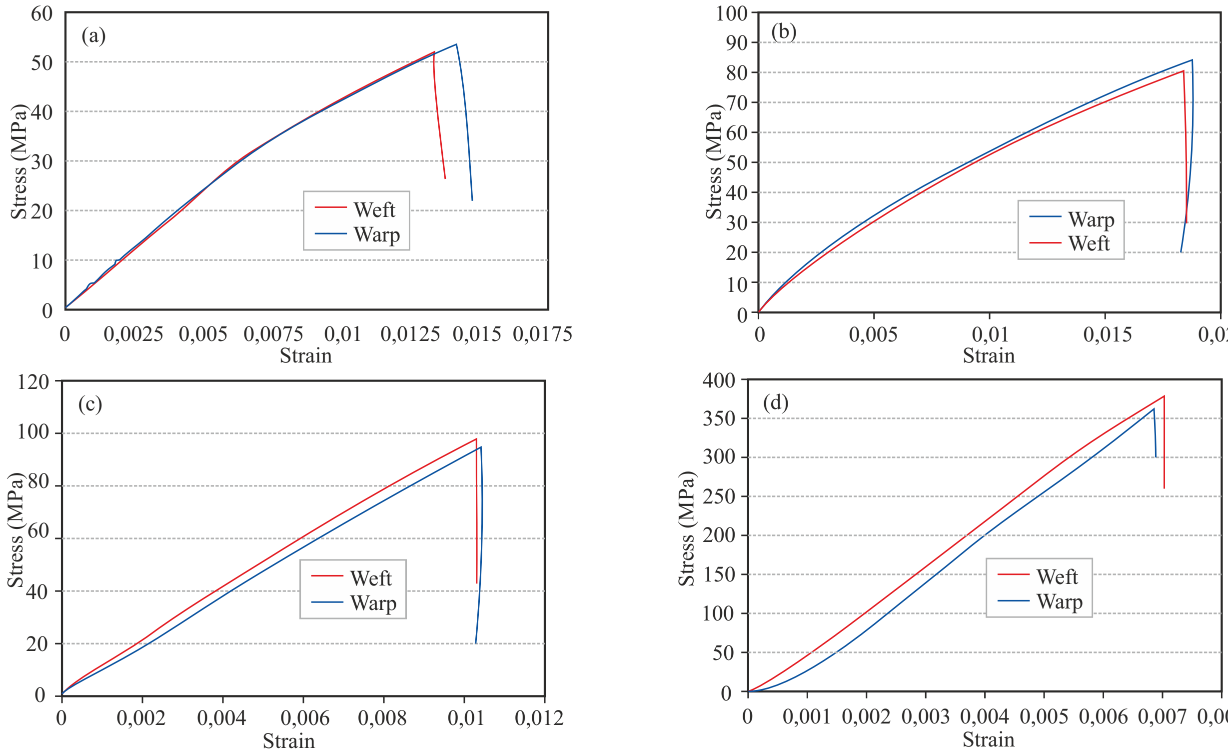

Figure 1 Stress-strain variations for different composite materials: (a) Sample C1; (b) Sample C2; (c) Sample C3; (d) Sample C4.

The tensile properties of a 100% carbon fiber composite material were measured for comparison with those of the hybrid composites. The tensile strength and Young's modulus of the carbon fiber composite are shown at ***Table 4***. Furthermore, the corresponding stress-strain curve is presented in ***Figure 1.d***. Initially, a linear characteristic was observed for the stress-strain response. However, as the load level increased, the curve became non-linear and showed a stiffening effect. This behavior is characteristic of carbon fibers, as indicated in the previous studies [5, 6]

The tensile strength of the carbon fiber composites was 4.7 times higher than that of the flax composites and 2.7 times higher than that of the jute composites. Similarly, the Young's modulus was 8 times higher than that of the flax composites and 5 times higher than that of the jute composites. These findings demonstrate that the mechanical properties of the natural fiber composites are too low and incomparable to those of carbon fiber composites.

The results obtained for the carbon-jute composites were lower than expected. The results re gathered in ***Table 4***, and the corresponding stress-strain curves are shown in ***Figure 1.c***.

The Young's modulus and tensile strength of the carbon-jute hybrid composites were higher than those of the 100% jute composite but still lower than expected. For the carbon-jute hybrid composite, the Young's modulus and tensile strength only increased by approximately 24% and 2.6%, respectively, relative to those of the 100% jute composite. The Young's modulus and tensile strength of the hybrid composite were, respectively, 4.2 times and 2.2 times lower than those of the 100% carbon fiber composite. Similar behavior for carbon-flax composites was reported by Dhakal et al. [7]. However, the tensile strength and Young's modulus can increase to a certain level by hybridizing, which holds for fibers that exhibit similar tensile strengths and Young's moduli. Combining a fiber that has high tensile strength and Young's modulus values with another that has lower strength and modulus values cannot provide the expected hybrid effect. This situation can be attributed to a split in the weak fibers, which eliminates their load-carrying ability. Consequently, it is clear that combining carbon and natural fibers cannot increase the tensile properties of the composites as expected. The slope of the stress-strain curve of C3 (***Figure 1.c***) supports this reasoning: there is no appreciable change in the slope of the stress-strain curve of the hybrid sample.

For natural fiber-reinforced composites, one of the most widely used materials is jute fibers. The results of tensile tests applied to jute-epoxy woven composites are presented in ***Table 4***, and the corresponding stress-strain curves for the warp and weft directions are presented in Figure 1.b. According to these results, the tensile strength of the jute-epoxy composites was measured to be approximately 110 MPa and the Young's modulus was measured to be approximately 9 GPa for 52% V_f. Compared with those of the flax composites, the tensile strength and Young's modulus of the jute-epoxy composites were 33% and 42% higher, respectively, for 52% V_f.

It is interesting that when the fabric strength values are compared with those of the composite materials, a serious decrease is observed. This situation can be explained by effect of the higher yarn crimp on the woven structure and the process temperature during composite production. The trend observed for the tensile strength between the dry fabrics and composites is quite different. The formation of the fabric structure may affect the tensile strength when it is in composite form. The structure may change due to factors such as tension and contraction during fabrication, which may not affect the properties of dry fabrics but may affect composites.

Impact properties of composite

The impact energies of the composites ranked as follows, in descending order: sample C4, sample C3, sample C1, and sample C2. The impact energies of samples C3, C1 and C2 were 36%, 58%, and 83% lower than the impact energy of sample C4, respectively. The impact strengths of the composites ranked as follows, in descending order: sample C4, sample C3, sample C2, and sample C1. The impact strengths of samples C3, C2 and C1 were 53%, 72%, and 76% lower than the impact strength of sample C4, respectively.

The strength and fracture toughness measured based on Izod and Charpy tests were calculated using equations 7 and 8. The results are shown in Table 5. The impact test results are very similar to the tensile test results. The flax-epoxy composites' impact strength and toughness values were 16% and 27% lower than those of the jute-epoxy composites. The carbon-epoxy composites showed the highest impact strength. Compared to those of the 100% flax-epoxy composites, the strength and fracture toughness were 3.1 and 5.8 times higher, respectively. Furthermore, the carbon-epoxy composites' impact strength and fracture toughness were 2.5 and 4.4 times those of the jute epoxy composites, respectively. These results show that carbon-epoxy composites with a high Young's modulus and strength also exhibit a much higher impact strength than that of natural fibers [5].

By hybridization, the impact strength and fracture toughness of the composites increased by a certain amount. Results prove that by hybridizing, the impact properties increased to a greater degree than did the tensile properties. Therefore, it can be concluded that jute fibers slightly increased the toughness of the composite materials. The jute-carbon hybrid composites' impact strength and fracture toughness improved by 65% and 51%, respectively, compared to those of the 100% jute material. However, the jute-carbon hybrid composite materials' impact strength and fracture toughness were 1.11 and 2.56 times lower, respectively, than those of the 100% carbon fiber composites.

Table 6

Experimentally determined impact toughness, water absorption and density of composites.

Samples	Impact Properties			Water Absorbtion (%)	
	Impact Energy (J)	Impact Strength (kJ/m^2)	Fracture Toughness (MPa.m$^{1/2}$)	After 2 h immersion	After 24 h immersion
C1	0.727 ± 0.05	6.291 ± 0.30	177.42 ± 6.92	0.192 ± 0.010	0.499 ± 0.030
C2	0.289 ± 0.05	7.292 ± 0.95	226.43 ± 8.83	0.376 ± 0.025	0.775 ± 0.041
C3	1.101 ± 0.22	12.059 ± 1.05	341.47 ± 3.19	0.200 ± 0.040	0.686 ± 0.035
C4	1.723 ± 0.25	25.843 ± 1.52	1215.8 ± 26.1	0.041 ± 0.018	0.050 ± 0.021

Water absorption

The water absorption of the composites after 24 hours of immersion ranked as follows, in descending order: sample C4, sample C2, sample C3, and sample C1. The water absorption values of samples C2, C3 and C1 were 46%, 52%, and 65% less than the water absorption value of sample C4.

Due to the extremely hydrophilic character of natural cellulosic fibers, the effect of their water absorption properties on their mechanical properties is a common research topic. Although water absorption generally improves mechanical properties such as the tensile strength and Young's modulus of cellulosic fibers in yarn form, water absorption causes a decrease when the fibers are used in composite materials. In composite form, absorbed water diffuses to the fiber-matrix interface and decreases the adhesion force, which causes a serious decrease in the mechanical properties of composite materials.

The water absorption properties of the composites are presented in ***Table 6***. The water absorption properties were evaluated according to the differences between the dry weight of the composite materials and their weight after 2 and 24 hours of soaking. According to the results, the natural fiber-reinforced composites exhibited very high water absorption values. The water absorption values of the flax-reinforced composites were 0.19% and 0.49% after being soaked for 2 and 24 hours, respectively. The water absorption values of the jute-reinforced composites were greater than those of the flax-reinforced composites. The water absorption values of the jute-reinforced composites were 95% and 55% greater than those of the flax-reinforced composites after soaking for 2 and 24 hours, respectively.

The water absorption values of the carbon-epoxy composites were very low. Specifically, the values were 3.9 and 8.2 times less than the water absorption values of the flax-reinforced composites after soaking for 2 and 24 hours, respectively. Similarly, the water absorption values of the carbon-epoxy composites were 8 times and 13 times less than the values of the jute composites after soaking for 2 and 24 hours, respectively. The water absorption values were observed to increase with hybridization. The water absorption values of the hybrid composites were 46% and 11% less than those of the jute-reinforced composites after soaking for 2 and 24 hours, respectively. The water absorption values of the hybrid composites were much higher than those of the carbon fiber composites. The water absorption values of the hybrid composites were 3.8 and 11.7 times greater than those of the carbon fiber composites after soaking for 2 and 24 hours, respectively.

It is well known that water absorption has a significantly negative effect on the mechanical properties of composite materials. Thus, such materials would not be suitable for applications that involve direct contact with water.

CONCLUSIONS

In this study, the properties of natural fiber woven fabric composites were investigated experimentally. The following results were obtained:

- The tensile strength and Young's modulus of jute-epoxy composites were 33% and 42% higher than those of flax-epoxy composites.

- The mechanical properties of carbon-epoxy composites were significantly higher than those of natural fiber composites. However, hybridization with carbon fiber made the hybrid materials stiffer, giving rise to stronger mechanical properties those of the jute fiber composite samples. This finding demonstrates that the hybridization of carbon and jute fibers can result in a composite material with improved tensile properties.

- The flax-epoxy composites' impact strength and toughness were 16% and 27% lower than those of the jute-epoxy composites. The impact strength and fracture toughness of the carbon-epoxy composites were significantly higher than those of the natural fiber composites. However, the results show that the hybridization of carbon and jute fibers can give rise to significantly improved impact properties.

- The water absorption values of the jute-reinforced composites were 86% and 55% greater than those of the flax-reinforced composite after soaking for 2 and 24 hours, respectively. The water absorption values were observed to increase with hybridization. Due to their remarkable sensitivity to moisture, the natural fibers examined in this study were determined to be easily influenced by environmental effects.

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