

ENHANCEMENT OF MECHANICAL BEHAVIOUR THROUGH HYBRIDIZATION OF KENAF WITH BASALT FIBER IN REINFORCED VACUUM BAGGED POLYMER COMPOSITE

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Many researchers concentrate on designing and developing natural hybrid fiber-reinforced composites due to their tremendous merits in terms of mechanical and thermal behaviors, and biodegradability. The present work developed hybrid composites using the vacuum bagging method with woven kenaf and basalt fiber reinforcement. Six hybrid composites, with five stacks in six different stacking sequences, were produced and compared with five stacks of layered composite made of individual basalt and kenaf fiber, respectively, to analyze mechanical properties, such as tensile, flexural, compression, impact, hardness, thickness swelling and water absorption, according to ASTM standards. Results revealed that the tensile, compressive and flexural properties, as well as water absorption (hydrophobic behaviour) and thickness swelling, of basalt fiber reinforced laminates were better compared with those of kenaf fiber-reinforced laminates and of kenaf and basalt fiber hybrids. Laminates with basalt fiber as the outermost layer showed good hardness and impact strength results. Morphological analyses were carried out on fractured composite samples, using scanning electron microscopy to study the failure modes.

Keywords: natural fiber-reinforced polymers, mechanical properties, basalt fiber, kenaf fiber, hybrid polymer composite

INTRODUCTION

Polymer matrix composites combine a polymer matrix and fiber reinforcements and serve as cost-effective and high strength-to-weight ratio materials in structural applications. Nowadays, natural fibers are utilized as reinforcements in polymer composites to develop eco-friendly, biodegradable, cost-effective materials to satisfy industrial needs.¹⁻⁴ Natural fiber-supported polymers have been examined extensively as a substitute for synthetic fiber composites and, under certain circumstances, metals. Natural fiber-reinforced composites have wider uses in many applications of their potential characteristics.⁵⁻⁷ Kenaf fiber, the most widely used natural fiber, has been revealed to have great strength, hardness, stiffness and biodegradability.⁸ There are many different types of natural fibers, but basalt has good strength, chemical stability and corrosion resistance.^{9,10} Originating from molten volcanic basalt rock, basalt fibers are made by spinning. The production of basalt fiber

does not necessitate the use of additives. This response lowers the danger of hazardous chemical exposure. Traditional techniques of manufacturing glass fibers, which need additives, are more ecologically friendly.¹¹ Much research was carried out to develop natural fiber reinforced polymer composites to replace synthetic fiber-reinforced polymers. The next sections address the investigation studies using natural fiber reinforcement in polymers.

The behaviour of composite materials can be influenced by the characteristics of the reinforcing elements, adhesives, stacking sequence and the size of each layer.¹² The tensile characteristics of basalt fibers were investigated, and it was found that, when used as a constituent element in composites, they have a significant impact on tensile strength.¹³ The mechanical properties of glass fiber polymers and basalt fiber polymers were studied. The mechanical testing findings revealed that basalt fiber reinforced polymers had

better characteristics than glass fiber reinforced polymers.¹⁴ Actually, the characteristics of basalt fiber reinforced polymers fall between those of polymers reinforced with E-glass fiber and those of polymers reinforced with carbon fiber.¹⁵ Composites produced by various methods, including the wet layup technique, gave similar performance.¹⁶ Due to the unique adhesive characteristics of basalt fiber, in relation to glass fiber, it has better mechanical properties, heat/humidity resistance, and alkali resistance.¹⁷ Hybridization of flax/basalt fiber laminates showed better performance in terms of impact behavior.¹⁸ Composite laminates made with kenaf fiber reinforcement presented enhanced tensile and flexural performance, compared to jute fiber-reinforced composite laminates.¹⁹ Also, the low-speed impact conduct and the consequent behaviors of glass/kenaf reinforced polymers with different weight proportions the constituents were studied. The composite made of glass/kenaf fiber in 3:1 fiber proportion exhibited improved impact characteristics, compared to the other composites made with different proportions.²⁰ The impacts on the mechanical characteristics of fiber-reinforced polymer composites by varying the fiber volume fraction were investigated, and a volume fraction of 25 to 27 percentage proved to be the most effective.²⁴ Moreover, the mechanical behavior of composites with fiber reinforcements is affected by the fiber–matrix interface and the stress transfer function, by which stress is transferred from the matrix to the fiber. Thus, it has been found that silane treated kenaf fiber-reinforced polymers display better performance in terms of mechanical behavior.²¹ Chemical treatment of natural fibers lessens the hydrophilic behavior of fiber and improves the adhesion between matrix and fiber, enhancing the mechanical properties of composites.²²

The above-mentioned studies highlight a few important aspects in the development of polymer-based composite materials reinforced with natural fiber. Basalt and kenaf fibers provide better results when used as polymer reinforcements in composites, and can have potential for structural and automotive applications. However, in the studies reported in the available literature so far, it appears that the characterization of the developed hybrid natural fiber-reinforced polymer composites has not been conducted sufficiently to offer data on some design and development aspects. In this research, kenaf and basalt fibers are used as reinforcement to develop hybrid

composites, containing five stacking layers with various stacking orders. The vacuum bagging method, which provides many advantages, including low cost and flexibility in operation,²³ was used to prepare the laminates. The tensile, impact, flexural and compression properties of the developed composites were studied. Morphological analysis using SEM was carried out to analyze the failure modes of fractured samples.

EXPERIMENTAL

Materials and methods

Two types of fibers were selected for developing composite laminates, with different stacking sequences, namely, kenaf and basalt fibers. Kenaf fiber, of 1.40 g/cm³ density, and basalt fiber, of 2.60 g/cm³ density, in the form of woven mats, were bought from M/s. Fiber Region, Chennai, India. The properties of basalt and kenaf fibers are listed in Table 1.²⁵ Epoxy resin LY556 and hardener HY951 were supplied by SM Composites, Chennai, India.

Fabrication process

The vacuum bagging method was utilized to develop the natural fiber reinforced hybrid composite laminates, using a 30 cm x 30 cm dimensions mold frame. The molds were covered with a glass plate to obtain a good surface finish on the laminate and a smooth flow of the resin in the mold. The trial and error method was used to obtain the optimum fiber volume fraction for preparing the composite laminates, with various stacking sequences. The optimal fiber volume fraction was varied between 0.22 and 0.35, and the mixing ratio of the matrix and the hardener was maintained at 10:1, as suggested by the supplier. The laminates were mould at room temperature. A deadweight of 25 kg was placed on top of the glass plate for a day during the curing process. Eight laminates were developed with various stacking sequences, as illustrated in Table 2. The laminates have been coded for simplicity of denotation. Table 2 shows the laminate code, the stacking sequence and the relevant fiber volume fractions in the composite laminates. The laminate codes K1 and B1 were taken as reference composites, corresponding to materials made of only kenaf fiber, and only basalt fiber, respectively. Equation (1) shows the fiber volume fraction formula:

$$\text{Fiber Volume Fraction, } f = \frac{\left(\frac{W_k}{\rho_k} + \frac{W_b}{\rho_b}\right)}{\left(\frac{W_k}{\rho_k} + \frac{W_b}{\rho_b} + \frac{W_m}{\rho_m}\right)} \quad (1)$$

where W_k , W_b and W_m are the weight of kenaf fiber, of basalt fiber, and of the matrix, respectively; ρ_k , ρ_b and ρ_m are the densities of kenaf fiber, basalt fiber, and of the matrix material, respectively.

Theoretical density was calculated using Equation (2):

$$\text{Density of composite, } \rho_c = \%m \times \rho_m + \%k \times \rho_k + \%b \times \rho_b \quad (2)$$

Experimental and theoretical densities of all the samples are shown in Figure 2.

Table 1
Properties of kenaf and basalt fibers

Property	Basalt fiber	Kenaf fiber
Density	2.75 g/cm ³	1.2-1.6 g/cm ³
Tensile strength (MPa)	1400-2300	220-930
Elongation at failure (%)	1.8-3.2	1.5-2.7
Elastic modulus (GPa)	89	15-53

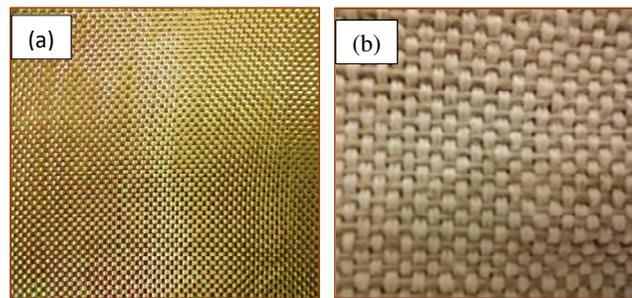


Figure 1: Basalt fiber mat (a) and kenaf fiber mat (b)

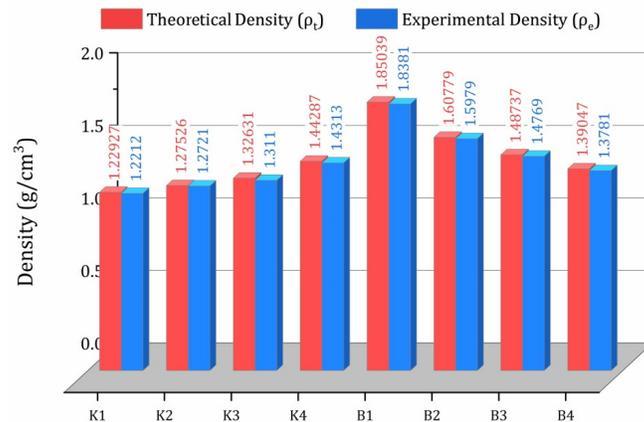


Figure 2: Theoretical densities and experimental densities of laminates

Table 2
Calculation of fiber volume fraction of composite laminates

No	Sample code	Stacking sequence	Weight (g)				Density (g/cc)				Fiber vol. fraction, <i>f</i>
			Composite, <i>W_c</i>	Kenaf fiber, <i>W_k</i>	Basalt fiber, <i>W_b</i>	Matrix material, <i>W_m</i>	<i>ρ_k</i>	<i>ρ_k</i>	<i>ρ_m</i>	<i>ρ_c</i>	
1	K1	KKKKK	375.95	119.2	0	256.75	1.4	2.6	1.15	1.221	0.28
2	K2	KKBKK	334.9	95.12	12.53	227.25	1.4	2.6	1.15	1.272	0.27
3	K3	KBKKB	307.78	71.42	25.11	211.25	1.4	2.6	1.15	1.311	0.25
4	K4	KBBBB	227.05	47.68	37.63	141.75	1.4	2.6	1.15	1.431	0.28
5	B1	BBBBB	129.6	0	62.6	67	1.4	2.6	1.15	1.838	0.29
6	B2	BBKBB	172	23.8	50.2	98	1.4	2.6	1.15	1.598	0.29
7	B3	BKBKB	197.1	47.9	37.6	111.6	1.4	2.6	1.15	1.477	0.33
8	B4	BKKKB	225.7	71.4	25.2	129	1.4	2.6	1.15	1.378	0.35

Mechanical characterization

A 50 kN load cell capacity-UTM Instron 3369 machine was utilized for the tensile, flexural and compression tests. The tensile characteristics of composites with different fiber stacking arrangements were determined by an ASTM D3039 tensile test, at the rate of 1 mm/min crosshead displacement and under ambient conditions. A three-point flexural test was conducted at a velocity of 1.5 mm/min across a length of 127 mm specimen based on the ASTM D790 standard. The compression test was done according to ASTM D 695 standard, with a 70 mm x 19 mm specimen size. The impact energy of an un-notched specimen of 65.5 mm x 12.7 mm was studied using the Izod test as per ASTM D256. In a Shore D hardness durometer, the Shore D hardness of the composites was determined as per ASTM D2240. From each laminate, for each stacking sequence, six samples were taken to test the above-mentioned mechanical characteristics. The average values were calculated for assessment of the results obtained from the tests.

Using the ASTM D570 standard, water absorption tests were carried out for the samples for various periods. The samples were weighed before and after immersion, at multiple intervals, until constant weights were obtained. According to ASTM D570, water absorption (%) was calculated by Equation (3). Thickness swelling (%) was also found using Equation (4) for all laminates:

$$\text{Water absorption (\%)} = \frac{W_i - W_o}{W_o} \times 100 \quad (3)$$

where W_i and W_o are the weight of composites before and after immersion, respectively;

$$\text{Thickness swelling (\%)} = \frac{T_i - T_o}{T_o} \times 100 \quad (4)$$

where T_i and T_o are the thickness of composites before and after immersion, respectively.

Scanning electron microscopy (JEOL JSM-6360LV) was used to examine the interaction between the fiber and the matrix since interfacial adhesion is an important factor that influences the mechanical strength of composite materials, as well as the mode of failure. The fractured samples were uniformly gold-coated before being tested.

RESULTS AND DISCUSSION

Tensile characteristics

The mechanical behavior of fiber-reinforced polymers is mainly influenced by the physical properties of fibers, fiber orientation, and interfacial adhesion between the matrix and the fiber.²⁶ The tensile test results and stress-strain curves of five-layer stacked hybrid composites made of basalt and kenaf fibers with different stacking sequences (K2, K3, K4, B2, B3, B4), as well as of the basalt fiber reinforced composite

B1, and of the kenaf fiber-reinforced composite K1, are shown in Figure 3. The five-layer basalt fiber-reinforced composite laminates (B1) exhibited a higher tensile strength, of 208.51 MPa, compared to the other laminates. Due to the excellent load transfer and tensile behavior of the basalt fiber made laminate B1, it has higher tensile strength than the other laminates. Similar results have been mentioned by B. Soares *et al.*¹⁵ On the other hand, the least value, of 33.94 MPa, was determined for the five-layer kenaf fiber-reinforced composite laminate (K1). This lower strength, compared to the other laminates, can be explained by the low elongation of kenaf fiber in all five layers.

All the laminates exhibited a linear relationship on the stress-strain curve. Among all natural fiber-reinforced hybrid composite laminates (K2, K3, K4, B2, B3 and B4), laminate B2 exhibited better results than the others. The superior tensile properties of laminate B1 are due to the higher tensile strength and strain rate of basalt fiber present in all layers of the laminate. Hybrid laminates K3 and B3 contain kenaf fibers and basalt fibers as the outer layers, respectively. Similarly, laminates K4 and B4 have the same outer layers as K3 and B3, respectively. Laminates K3 and B4 have the same proportion of the two fibers in their configuration. This is also true for the configuration of laminates K4 and B3.

According to the results, the laminates with kenaf fiber as the outer layer produce better results than the laminates with basalt fiber as the outer layer, as displayed in Figure 3 (a). Thus, K3 has a tensile strength value of 64.05 MPa, greater than that of B4 – of 51.31 MPa. Also, the tensile strength of the K4 laminate is 91.81 MPa, greater than that of the B3 laminate, 85.78 MPa. This demonstrates that kenaf fiber used as the outer layer of the laminate imparts high tensile strength to composites. A similar phenomenon was observed by Fragassa *et al.*²⁷ Alkali treated fiber improved the interfacial bonding between epoxy resin and fiber. Alkali treatment of kenaf fiber improved the wettability and also reduced its hydrophilic nature by removing the moisture content present on the surface of the fiber. Moreover, it increased the surface roughness of the fiber. The higher surface roughness improves the interfacial adhesion between the epoxy resin and kenaf fiber. Thus, kenaf fiber as the outermost layer produced good mechanical

strength due to the interfacial adhesion between the matrix and kenaf fibers, as the rough surface of natural fibers allows the epoxy resin to spread along the openings of the fiber layers. The ability of the laminate materials to transmit stress was improved by appropriate epoxy resin bonding, indicating that kenaf fiber can replace basalt fiber in laminates, especially in the outermost layer, providing high tensile strength materials. A similar observation was reported in a hybrid composite with kenaf and banana fiber by P. Samive *et al.*²⁸ The same phenomena were observed in the K3 and B4 laminates, which have the same number of kenaf and basalt layers, indicating that hybridizing the fibers produces good tensile characteristics.^{28,19}

Flexural strength

A three-point bending test was done on the composite laminates to find their flexural properties. The results showed that laminate B1 has better flexural strength – of 212.02 MPa, and flexural modulus – of 7237 MPa, which are higher than those of the other laminates. This can be explained by the fact that in B1 all the layers were made up of basalt fiber reinforcement, which naturally has higher elongation and load transfer, as reported in a previous study on basalt/jute fiber-reinforced polyester composites by P. Amuthakkannan.²⁹ Kenaf fiber in the skin layer and basalt fiber in the core and adjacent layers improve the flexural properties. It is noted in laminates K3 and K4, which have basalt fiber in the middle and adjacent layers and kenaf fiber as the outermost layers. A similar observation was reported for kenaf–aramid hybrid composites by R. Yahaya.³⁰

The five kenaf fiber layer reinforced hybrid composite laminate K1 gives very low flexural strength, compared to the other laminates, while laminate K2 gave poorer flexural modulus than the other laminates. When comparing all the laminates containing an equal number of basalt and kenaf fiber layers, with different configurations, (laminates B3 vs. K4, and laminates K3 vs. B4), it appears that an alternating order of fiber layers in hybrid composites does not enhance the flexural properties. Also, it is mainly noted that kenaf fiber used as the outermost layers in hybrid composites have higher flexural properties than in the case of basalt fiber in the outermost layers. This is in agreement with the findings of Khan *et al.*¹⁹ and Vijaya Ramnath *et al.*³¹ The flexural

strength and flexural modulus of composite laminates are displayed in Figure 3 (c) and (d), respectively.

Compressive strength

According to G. Santosh Gangappa, basalt fiber improves the compressive strength of laminates.³² A similar observation was made in our study, when examining the compressive strength results of the basalt/kenaf reinforced hybrid laminates. Laminate B1 has a compressive strength of 27.94 MPa, by 13.43% higher than that of its counterpart laminate K1 – with a compressive strength of 24.63 MPa. Hybridizing and stacking sequence of fiber layers positively impact the compressive strength of the laminates (Fig. 3e), by contributing to absorbing a higher compressive force (in contrast to laminate K1). Similar observations were reported by P. Sathyaseelan.³³ From Figure 3 (e), it is noted that the laminates with kenaf fiber as the outermost layers (K3 and K4) produce higher compressive strength than those with basalt fiber as the outer layers (B3 and B4). The above observations are also valid for the laminates with equal numbers of basalt and kenaf layers (comparing laminates K4 vs. B3 and laminates K3 vs. B4). Thus, kenaf fibers used as the outer layers in hybrid composites provide higher compressive strength than basalt fiber as the outer layers in hybrid laminates.

Impact strength

Izod impact tests were carried out on the composite samples to analyze their impact characteristics. High-energy absorbing basalt fiber improves the hybridized composites' impact strength.³⁴ Among all the laminates, B2 has the highest impact energy absorption characteristics. Specifically, laminate B2 has an impact strength of 71.14 KJ/m², which is 5.27% and 93.84% higher than the values obtained for laminates B1 and K1, respectively. It indicates that kenaf fiber used as the core and basalt fiber as surface layers provides good impact strength properties. Meanwhile, an increase in basalt fiber content enhances the impact strength properties. The situation mentioned above can also be noted in laminates B3 and B4, which have basalt fibers as the surface layers, compared with K4 and K3, respectively. This suggests that basalt fiber at the surface has more load transferring capacity. Another reason for this improved performance can be the alternating arrangement of the fiber

layers in these laminates (B3 vs. K4, K3 vs. B4).³³ A comparison of the impact strength of the

composites is shown in Figure 3 (f).

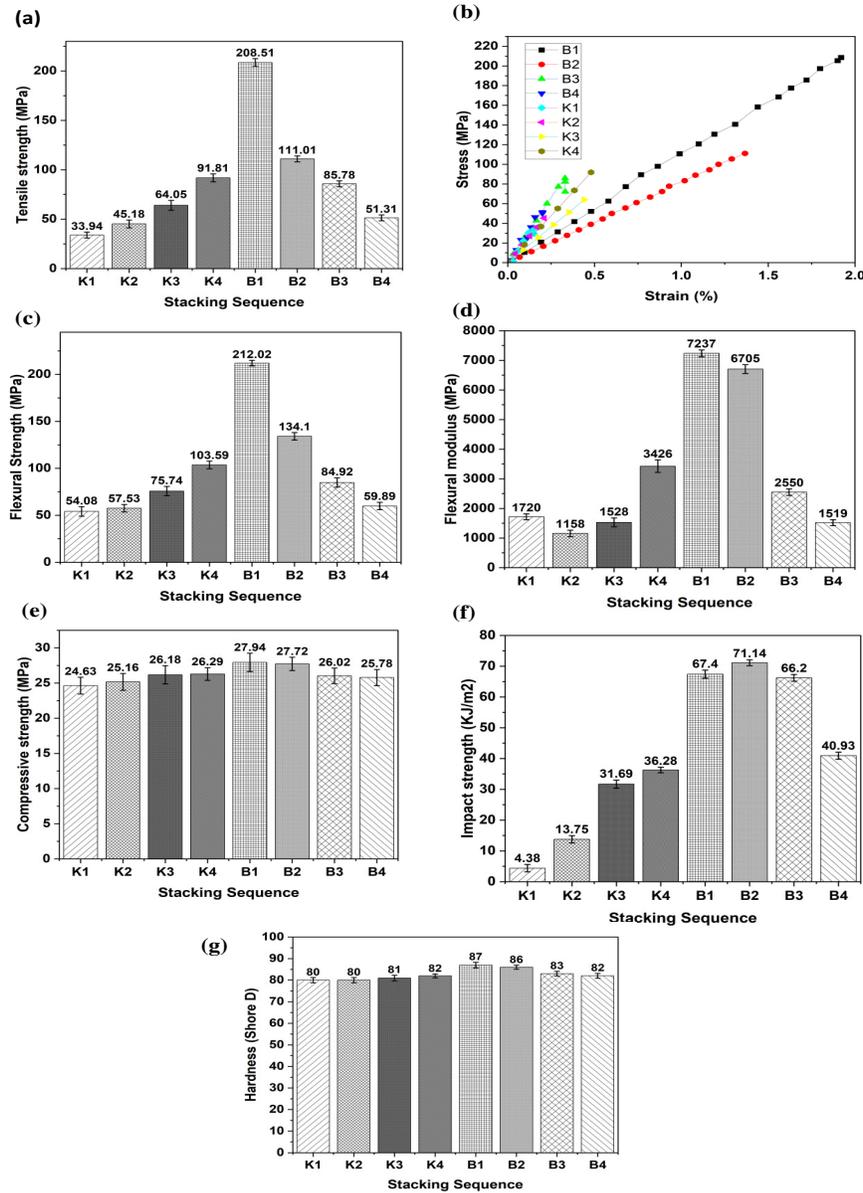


Figure 3: (a) Tensile strength, (b) Stress-strain curves, (c) Flexural strength, (d) Flexural modulus, (e) Compressive strength, (f) Impact strength, and (g) Hardness comparison chart of composites

Hardness

Figure 3 (g) indicates that laminates with basalt as the outermost layer present high hardness values. This implies that specimens with basalt fiber as the outermost layer may withstand more aberration and penetration than composites with kenaf fiber as the outermost layer, due to the higher hardness of basalt fiber, compared to that of kenaf fiber.³⁵ Laminate B1 has five basalt fiber

layers that give a high hardness value – of 87, which is 8.75% more than those of laminates K1 and K2. The K1 and K2 have kenaf fiber as the skin layers and the successive layers produced a much lower hardness value than in all other laminates.³⁶ The laminates with basalt fiber as the skin layer revealed better performance in impact and hardness properties,^{37,38} exhibiting less fiber breakage and low matrix fretting. The same

phenomena have been reported by R. Naveen³⁷ and M. A. Abd El-baky.^{39,40}

Water absorption test

As illustrated in Figure 4 (a), the five kenaf fiber layer reinforced composite (K1) has a high level of water absorption. On the other hand, the five basalt fiber layer reinforced material gives very low water absorption, as basalt fiber is hydrophobic. The water absorption of the K1 laminate is by 171.35% higher than that of B1. Actually, the water absorption value increased with increasing kenaf fiber loading in the laminate. Water absorption is enhanced in composites with natural plant fiber content. Blending more resilient basalt fiber with kenaf fiber in a hybrid composite makes an efficient reinforcement that increases the natural fiber composite's durability under different climatic conditions. Similar observations have been made by Moethwe.³⁸ Adding synthetic basalt fiber to kenaf fiber in hybrid laminates is an efficient way for reducing water absorption.

Thickness swelling

Figure 4 (b) reveals that higher kenaf fiber content increases the thickness swelling percentage. The thickness swelling percentage in laminate K1 is 82.25% higher than that of laminate B1. Laminate K1 (kenaf only) exhibits more thickness swelling than the hybrid laminates (K2, K3, K4, B2, B3 and B4). This means that hybridizing the reinforcing fibers reduces the water absorption as well as the thickness swelling. It was also observed that thickness swelling increases when the water absorption time rises.

The swelling of the fibers puts stress on the surrounding matrices, causing micro-cracking and ultimately catastrophic failure of the composite.³⁹

Morphological analysis

The tensile tested specimens of hybrid laminates B2 and K2 were examined using SEM for determining their failure modes, and Figure 5 (a-b) illustrates the fracture surfaces of these hybrid laminates. As can be seen in Figure 5 (b), the matrix crack is initiated in the specimen, because of the voids and poor adhesion between the matrix and the fiber in the laminate. Fiber pull-out, fiber breakage and crack initiation make the sample subjected to the tensile test fail. As a result, load transmission between the fibers was poor. Tensile fractured B2 specimens have less pull-out and exhibit good bonding between the fiber and the matrix, as can be observed in Figure 5 (a). The hybrid composite laminate K2 subjected to the flexural test exhibited failure because of delamination, kinking and bending of the fiber (Fig. 5 d) – this led to the specimen exhibiting poor load transfer. Laminate B2 had less fiber bending and delamination, and thus, it exhibited better stress transfer. In comparison with the composites containing basalt fabrics at the core, those with basalt fabrics as skin layers had lower flexural strength and modulus. Also, they exhibited a fracture surface with long fibers pulled out and numerous delaminations. This suggests that the fracture characteristics of the outermost layer determine the flexural response of the composite as a whole, as also reported by I. D. G. Ary Subagia.⁴¹

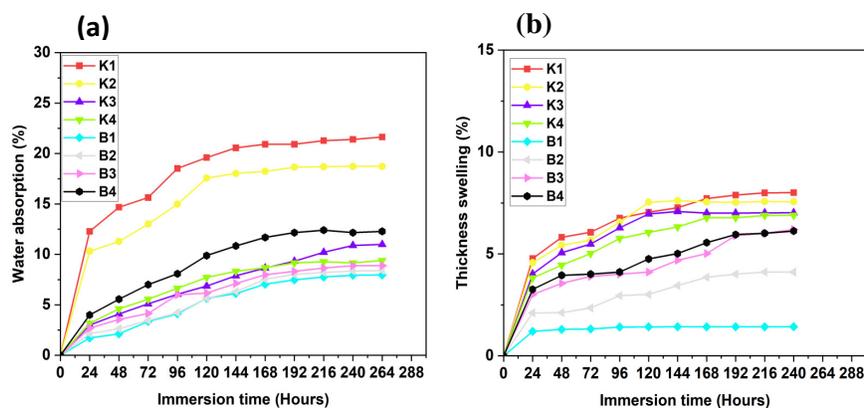


Figure 4: (a) Water absorption percentage and (b) Thickness swelling percentages of composites

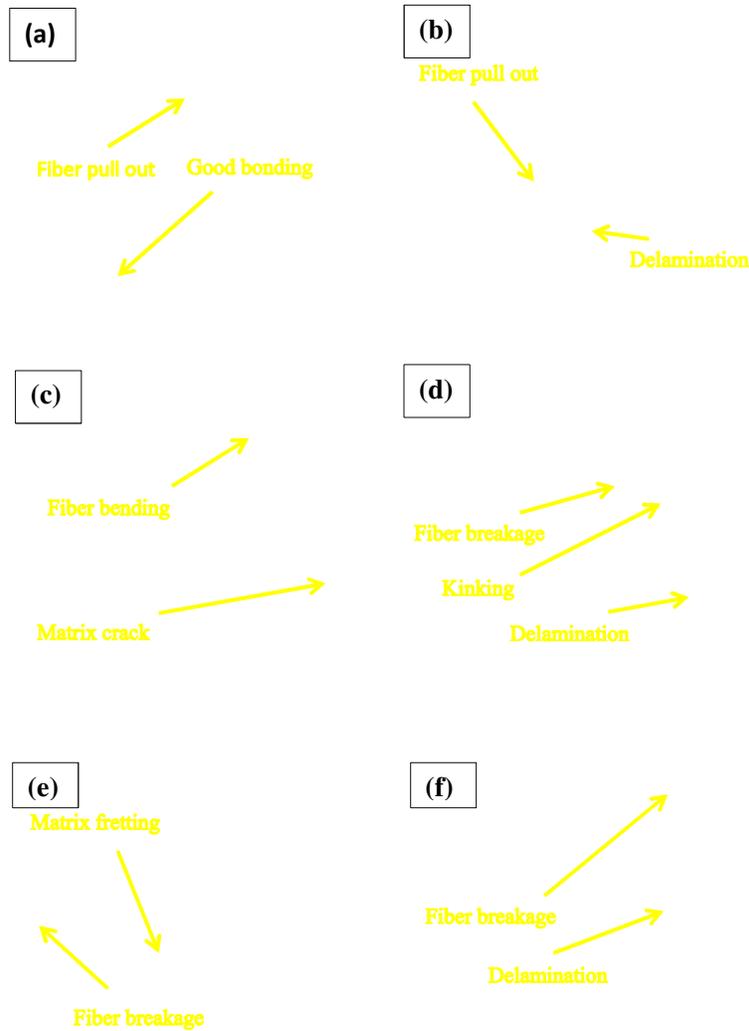


Figure 5: SEM images of fractured surfaces of (a) tensile tested B2 specimen, (b) tensile tested K2 specimen, (c) flexural tested B2 specimen, (d) flexural tested K2 specimen, (e) impact energy tested B2 specimen, (f) impact energy tested K2 specimen

Impact load causes the specimens of B2 and K2 laminates to fail, because of cracking, breaking of the fibers and crumbling of the matrix, as can be observed in Figure 5 (e and f). It may be also noticed that, while the matrix collapsed under the impact force, many of the fibers still remained intact.

CONCLUSION

Basalt and kenaf fiber reinforced epoxy composites, with various stacking sequences, were fabricated using the vacuum bagging technique. The fabricated samples were tested in

accordance with the ASTM standards for determining their tensile, compression, flexural, impact and hardness properties, as well as their water absorption and thickness swelling behaviors. Fractured specimens were analyzed using SEM for examining their morphology and failure modes.

The following findings of the research can be formulated:

- (i) Laminate B1, which contained five layers of basalt fiber, exhibited excellent tensile, compressive, flexural strength and hardness, among all the laminates. This is due to the

excellent tensile behavior of basalt fibers in all the layers of the composite, providing exceptional load transfer.

(ii) Among all the hybrid laminates, the laminates with kenaf fiber as the surface layers revealed better tensile, compressive and flexural properties than the laminates with basalt fiber as the surface layers.

(iii) The laminates with basalt fiber as the outermost layers revealed better performance in terms of impact and hardness properties than the laminates with kenaf fiber as the surface layers, considering all the hybrid laminates. However, due to the good load transferability of basalt fiber, the hybrid laminates with basalt fiber at the surface had good impact strength and hardness.

(iv) Laminate B2 had the highest impact strength value – of 71.14 kJ/m². This can be explained by the increased load transfer characteristic of basalt fiber used as the outermost layer and in the successive layers of laminates. Moreover, it is also due to good adhesion between the matrix and the fiber.

(v) Laminates with kenaf fiber showed enhanced water absorption characteristics, because of the hydrophilic behavior of natural kenaf fiber. Because of this, an increase in the kenaf fiber content in the laminates enhances their water absorption characteristics. In contrast, the presence of basalt fiber in the hybrid composites caused an opposite behavior. Also, with more significant water absorption of kenaf fiber reinforced hybrid polymers, their thickness swelling also increased.

(vi) SEM analysis revealed fiber pull-out, matrix cracking and fiber breakage as causes leading to the failure of the tensile-tested composites. In contrast, in flexural tests, the laminates demonstrated delamination and fiber bending. In the impact tests, the failure is mainly caused by fiber breakage and crumbling of the matrix.

From the above-mentioned experimental results, it can be concluded that basalt fiber reinforcement in hybrid composites improves the mechanical characteristics of the materials. Hybrid composite laminates with kenaf fiber as the outermost layers achieved good tensile, flexural and compressive strength properties. As regards the impact and hardness properties, the composite laminates with basalt fiber

reinforcement used as the outermost layers exhibited superior performance.

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