

Partial Replacement of Glass Fiber by Woven Kenaf in Hybrid Composites and its Effect on Monotonic and Fatigue Properties

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Natural–synthetic fiber hybrid composites offer a combination of high mechanical properties from the synthetic fibers and the advantages of renewable fibers to produce a material with highly specific and determined properties. In this study, plain-woven kenaf/glass reinforced unsaturated polyester (UP) hybrid composites were fabricated using the hand lay-up method with a cold hydraulic press in a sandwich-configuration laminate. The glass was used as a shell with kenaf as a core, with an approximate total fiber content of 40%. Three glass/kenaf weight ratios percentages of (70/30)% (H1), (55/45)% (H2), and (30/70)% (H3) were used to fabricate hybrid composites. Also pure glass/UP and kenaf/UP were fabricated for comparison purposes. Monotonic tests, namely tensile, compression, and flexural strengths of the composites, were performed. The morphological properties of tensile and compression failure of kenaf and hybrid composites were studied. In addition, uniaxial tensile fatigue life of hybrid composites were conducted and evaluated. The results revealed that the hybrid composite (H1) offered a good balance and the best static properties, but in tensile fatigue loading (H3) displayed low fatigue sensitivity when compared with the other hybrid composites.

Keywords: Woven roving glass; Woven kenaf; Natural fibers; Hybrid composites; Mechanical properties; Fatigue life assessment

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INTRODUCTION

Modern technologies in structural and transportation applications, especially related to aerospace, require a typical combination of material properties that cannot be achieved by metal and ceramics alone. Excellent structural competency requires high specific strength and high specific stiffness of materials, qualities that cannot be obtained using conventional materials. Composites help achieve desired properties by combining unique materials in an alternative way. Generally, they possess high specific strength and high specific modulus, which makes them useful in various industrial applications. For instance, glass and carbon fiber polymer composites have widespread applications in modern industries (Nunna *et al.* 2012).

In spite of all the favorable properties of synthetic fiber polymer composites, there are many limitations, such as recycling, biodegradability, and other environmental issues

at the end of their life (Thakur and Thakur 2014). Because of this, it is necessary to discover applicable alternatives to minimize the usage of synthetic fibers (Thakur *et al.* 2014). Research has shown that natural fibers reinforced with polymer “bio composites” are a good alternative because of their biodegradability, renewability, low cost, density, and reasonable specific mechanical strength (Thakur and Singha 2010; Salman *et al.* 2016). However, many studies suggest that the natural fibers have disadvantages, such as poor moisture resistance, compared with synthetic ones (Akil *et al.* 2011).

Hybridization is a combination of natural and synthetic fibers into one matrix, offering better composites with the advantages of both fibers. This can result in a higher strength-weight ratio, enhanced fatigue life, and improved mechanical properties compared with single-fiber composites (Jawaid and Abdul Khalil 2011; Salman *et al.* 2015a). In the past few years, many researchers have studied the hybridization of natural fibers with glass using various fiber architectures and orientations, depending on the studied properties and tests conducted. For instance, flax/glass (Arbelaiz *et al.* 2005), oil palm/glass (Khalil *et al.* 2007), hemp/glass (Poathan *et al.* 2007), jute/glass (Ahmed and Vijayarangan 2008), kapok/glass (Reddy *et al.* 2008), banana/glass (Poathan *et al.* 2010), sisal/ glass (Ornaghi *et al.* 2010), coir/glass (Wong *et al.* 2010), palf/glass (Devi *et al.* 2010), and non-woven kenaf /glass (Atiqah *et al.* 2014) composites have been reported. The main point of these studies is to reduce the usage of synthetic fibers and to achieve higher properties for final hybrid composites.

Rajulu and Devi (2007) studied the compressive properties of treated and untreated ridge gourd/glass reinforced UP sandwich hybrid composites and found that the compressive strength of the composite was affected significantly by hybridization and slightly by chemical treatment. Another study carried out by Park and Jang (2000) assessed the effect of stacking sequence of impacted aramid/glass reinforced vinyl ester hybrid composite on compressive strength. Ahmed and Vijayarangan (2008) investigated the mechanical properties of woven jute/glass hybrid reinforced polyester with various structures and found that the best performance was obtained in a sandwich structure where glass was the shell and jute was the core; a similar conclusion was reported also by Amico *et al.* (2008), Gujjala *et al.* (2014) and Sharba *et al.* (2015). Bagheri *et al.* (2013) studied the mechanical properties of woven flax/carbon reinforced epoxy sandwich hybrid composites and reported that the hybrid possess a considerable ultimate strength in both tension and flexural loading. Recently, Yahaya *et al.* (2014) carried out experiments on the physical properties of woven kenaf/Kevlar reinforced epoxy hybrid composites for impact applications. The properties studied in their work include tensile, flexural, and impact strengths; the results showed that replacing 22% of Kevlar by weight with kenaf offered improved mechanical properties compared with other hybrid composites. The same conclusions were confirmed by Júnior *et al.* (2012). In terms of woven kenaf reinforced polymer, a few studies have characterized some of the physical properties, as reported by Salman *et al.* (2015b), Dan-Mallam *et al.* (2014), and Rashid and Hani (2013). Although many researchers have explored the mechanical properties of natural fibers, there have been few studies focusing on the woven structure of these fibers, especially in the hybrid composites field.

There have been limited studies on natural fiber hybrid composites with woven structures and even fewer reports on the cyclic fatigue assessment of natural-synthetic hybrid composites. Research on kenaf fiber is especially scarce, even with increasing interest in its utilization as reinforcement for structural applications. Thwe and Liao (2003) investigated the effect of hybridization on the durability of bamboo/glass reinforced

polypropylene hybrid composites in a sandwich structure. While the results regarding the fatigue of hybrid composites were limited, it was concluded that the hybridizing process improved the fatigue life of bamboo-based composites. Bagheri *et al.* (2014) studied the fatigue life of unidirectional flax/carbon reinforced epoxy hybrid composites for medical applications. In this study, a non-destructive method, using an IR-camera and morphological assessment, was used to predict the high cyclic fatigue strength of the hybrid composites. Although no comparison with pure flax or carbon fiber-based composites was available, an improvement in fatigue strength was found compared with previous work on pure flax. Shahzad (2011) reported the hybridization of chopped mat hemp fibers and glass as reinforcements for unsaturated polyester and the fatigue strength of the composites; the hybrid composites were fabricated in a sandwich configuration. Although the fatigue strength of the composites was enhanced by adding glass fiber, no improvement in fatigue sensitivity was observed.

This study is an attempt to answer the frequent question of how the replacement of glass fabric by woven kenaf fabric generally will affect the monotonic properties and particularly the fatigue life and fatigue sensitivity of final hybrid composites. Therefore, in this work, a partial replacement of glass fiber by woven kenaf fabric in reinforced unsaturated polyester was carried out. The replacement was achieved in three stages of hybrid composites, and pure kenaf- and pure glass-reinforced composites were fabricated for comparison purposes. Tensile, compressive, and flexural properties along with uniaxial tensile fatigue life of hybrid composites were evaluated; also, a morphological study was conducted to highlight fracture modes that occurred with various loading conditions.

EXPERIMENTAL

Materials

Woven roving kenaf fiber, used as reinforcement in this study, was supplied by ZKK. Sdn. Bhd, Malaysia. The fiber was placed in an oven to remove moisture before fabricating the composites. The synthetic reinforcement fiber used in this work is woven glass, with orthophthalic unsaturated polyester as a binding resin mixed with 1.5% of catalyst. Figure 1 shows the materials used to fabricate kenaf/glass hybrid composite laminates.

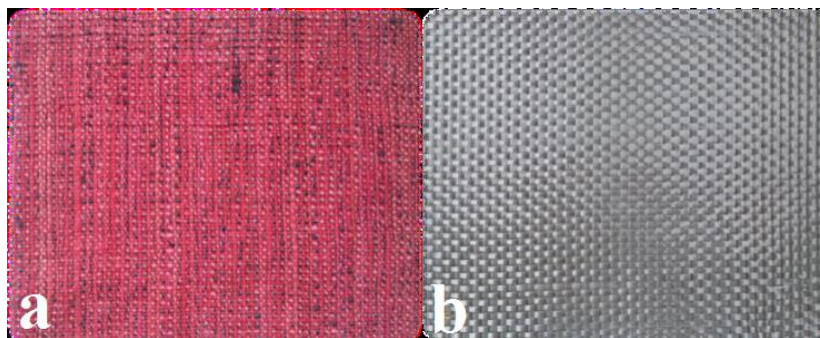


Fig. 1. Reinforcements used to fabricate hybrid composites (a) Kenaf and (b) glass fabrics

Fabrication of the Composites

A combination of hand lay-up and hydraulic cold press methods was conducted to fabricate the hybrid composite laminates used in this work. Kenaf fabric was dried in a

ventilated oven at 105 °C for 24 h to remove moisture. The moisture content was measured for five samples, and the average value was found to be 8.3% of the total weight of the fiber. The unsaturated polyester was mixed with 1.5% catalyst and then poured on each layer of fabrics. Then, a roller was used to separate the resin along the layers and push the air bubbles out of the surface. After laying-up the reinforcements, the mold was closed and placed under a cold press for 1 h. The mold was then cured inside an oven for 2 h at 80 °C, which is the curing temperature of unsaturated polyester. Finally, it was left to cure at room temperature for 48 h before the composites were cut to the required dimensions for testing. The fiber volume fraction of composites was kept at approximately 35%. The glass:kenaf weight ratios initially selected in this study were pure glass, 70:30 (H1), 55:45 (H2), 30:70 (H3), and pure kenaf in a symmetric sandwich configuration.

The experimental density of composites was measured using Archimedes' approach following ASTM D-792 (1997) with distilled water and a sensitive digital balance. Five samples were measured, and the average value was recorded. The void contents of composites were determined using Eq. 1 (Dhakal *et al.* 2007; Sharba *et al.* 2016b). Table 1 shows the designation, composition, and specifications of all the composite laminates fabricated,

$$\text{Void content (\%)} = 1 - \rho_c \left[\frac{W_{f1}}{\rho_{f1}} + \frac{W_{f2}}{\rho_{f2}} + \frac{W_m}{\rho_m} \right] * 100 \% \quad (1)$$

where W_f and W_m are the weight fractions of fibers and matrix, respectively, and ρ_c , ρ_f , and ρ_m are the densities of the composite, fibers, and matrix, respectively.

Table 1. Designation and Specifications of Hybrid Composites

Composite Type	Fiber Weight Ratio (%)		Fiber Fraction (%)		Experimental Density (g/cm ³)*	Void Content (%)*	Thickness (mm)
	Glass	Kenaf	Weight	Volume			
Glass	100	0	58.3	38.8	1.66 (0.003)	1.2 (0.55)	2.32
H1	70	30	49.7	37.5	1.41 (0.012)	1.4 (0.40)	3.15
H2	55	45	46.6	36.8	1.33 (0.005)	2.3 (1.40)	4.57
H3	30	70	39.0	32.5	1.15 (0.022)	7.9 (0.27)	5.42
Kenaf	0	100	34.0	33.5	1.11 (0.011)	4.9 (0.08)	5.17

* Values in parentheses are the standard deviation

Testing Procedures

Tensile

Tensile loading tests were performed using a universal testing machine (model 3382 with Bluehill software, Instron, USA) equipped with a 100-kN load cell at a crosshead speed of 2 mm/min. The specimens used were 250 mm in length, 25 mm in width, and 170 mm in gauge length. The test procedure followed ASTM D-3039 (1995b). Emery cloth was used as tabs for samples with a thickness less than 3 mm to prevent slipping. Six

specimens were tested from each group of composites, and their values were averaged and recorded.

Compression

The compressive strength of composites was tested with an Instron machine (model 3382 with Bluehill software, Instron, USA) equipped with a 100-kN load cell and cross-head speed of 1 mm/min according to ASTM D-3410 (1995a). Six samples of each composite were tested with dimensions of 140 mm in length, 15 mm in width, and gauge length of 13 mm. Emery cloth was used as tabs for samples with thickness less than 3 mm to prevent slipping. The gauge length was kept at a minimum to prevent buckling during compression loading. The average values of compressive strength were recorded.

Flexural

A three point-bending test was achieved with an Instron machine (model 3366 with Bluehill software, Instron, USA) with a 5-kN load cell and cross-head speed of 2 mm/min according to ASTM D-790 (1997). Five rectangular specimens were tested from each composite with dimensions of 120 mm in length and 13 mm in width; the span to depth ratio used was 16:1, and the average value was determined. The test samples were carefully cut from each laminate to the required shape using a wheel saw.

Fatigue

The fatigue test procedure was conducted according to ISO 13003 (2003). Twelve fatigue specimens with dimensions of 250 mm by 25 mm with a gauge length of 150 mm were prepared and glued to aluminum tabs with thicknesses of 1.5 mm. A uniaxial tensile (tension-tension) cyclic loading test was performed using a servo-hydraulic universal testing machine (model 8874 with wave matrix fatigue software, Instron, USA) equipped with a 30-kN unit cell under load control, with a selected stress ratio of (0.1) and a frequency of 10 Hz. The test was performed at four stress levels: 40%, 50%, 60%, and 70% of the ultimate tensile stress (UTS) of the composite.

In addition, an IR thermographic camera (Flex-Cam model Ti45, Fluke Corporation, WA, USA) with a detector resolution of 160 × 120 resolution and a 20-mm lens was used to monitor the specimen temperature during fatigue testing, as recommended by the standard. A linear regression equation was used to fit the experimental fatigue data to determine the fatigue coefficients of the materials after plotting the normalized Wohler stress-life (S-N) diagram (Eq. 3),

$$\sigma_{max} / \sigma_0 = b \log N \quad (3)$$

where σ_{max} is the maximum applied stress, σ_0 is the static ultimate strength, N is the number of cycles to failure, and b is the fatigue strength coefficient.

Morphology

A scanning electron microscope (SEM) was used on selected failed samples to study the morphological behavior of tensile failure sections and to obtain more details about the fracture modes for the various kenaf structures used. In addition, the SEM can show the compatibility between the glass, kenaf fibers, and unsaturated polyester matrix. The experiments were conducted using a model S-3400N PC-based variable pressure SEM (Hitachi, Japan).

RESULTS AND DISCUSSION

Static Properties

Figure 2 shows the stress-strain relationships for pure kenaf and pure glass composites, as well as the behavior of kenaf/glass hybrid composites. The ultimate tensile strength, elastic modulus, and elongation at break were obtained from these relationships. The first observation is apparent from Fig. 2 is that the hybridization effect matched the hybrid mixture rule: as more glass was added, higher mechanical properties were obtained. The kenaf fabric reinforced polyester showed a considerable ultimate strength, up to 40 MPa, and an elastic modulus of 5 GPa. The mechanical properties of woven kenaf were higher than previous reports on untreated and alkaline-treated woven kenaf (Yahaya *et al.* 2014, 2015) and kenaf mat composites (Fiore *et al.* 2015). However, these studies used an epoxy matrix, which has a higher strength than the UP used in this study. Stress-strain curves determined that all composites had a linear relationship in their elastic zone, ended by catastrophic brittle failure by complete fiber fracture. This means that kenaf and glass fibers had a good adhesion with the matrix and successful stress transfer occurred.

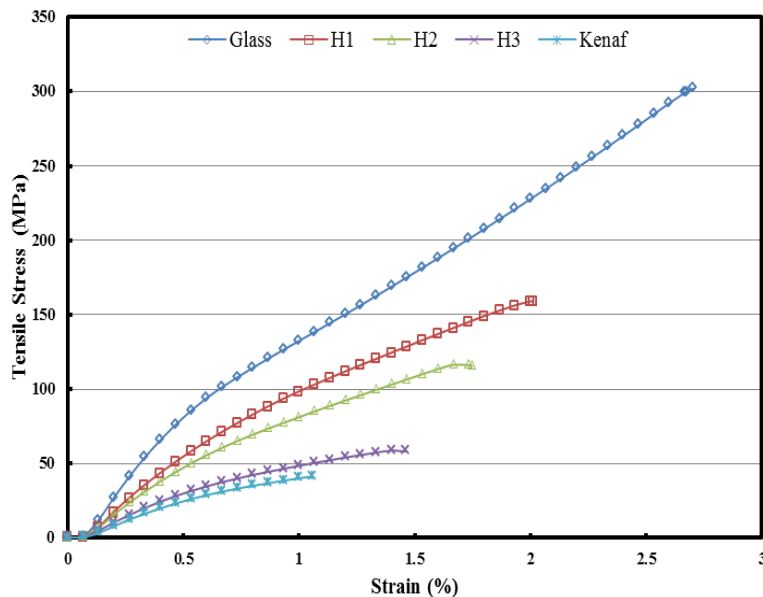


Fig. 2. Tensile stress- strain curves for composites

Figure 3 depicts the tensile properties of the composites formed in this work. The hybridization of kenaf glass fabrics successfully improved the mechanical properties of composites. It was observed that replacing 30% of glass weight with kenaf (H1) reduced the composite strength by 46% compared with pure glass/UP. By replacing 45% of the glass with kenaf in (H2) hybrid composites, there was a 61% reduction in tensile strength of composite. Finally, using 70% kenaf and 30% glass in (H3) hybrid composites resulted in drastic reduction with more than 81% in tensile strength compared with glass composite. Furthermore, similar trends were observed for tensile modulus, elongation, and density of the composites. However, the modulus of H3 and kenaf/UP had the same value because of the high ratio of kenaf in H3. On the other hand, the specific properties of hybrid composites increased with decreasing density of composites; the density was reduced by 15%, 20%, and 31% for H1, H2, and H3, respectively, compared with that of pure glass/UP. The trends for tensile properties of composites with respect to kenaf fiber ratio are shown

in Fig. 3. Generally, it can be concluded that the replacement of glass by 30% woven kenaf (H1) presented the best mechanical properties compared with other hybrid composites.

Figure 8 provides an overall comparison among all mechanical tests performed through replacement process. The results shown confirm that H1 composites offered the minimum reduction and higher improvement in mechanical properties when compared to both glass/UP and kenaf/UP composites respectively. Moreover, these findings are supported by the conclusions drawn by Júnior *et al.* (2012) and Yahaya *et al.* (2014).

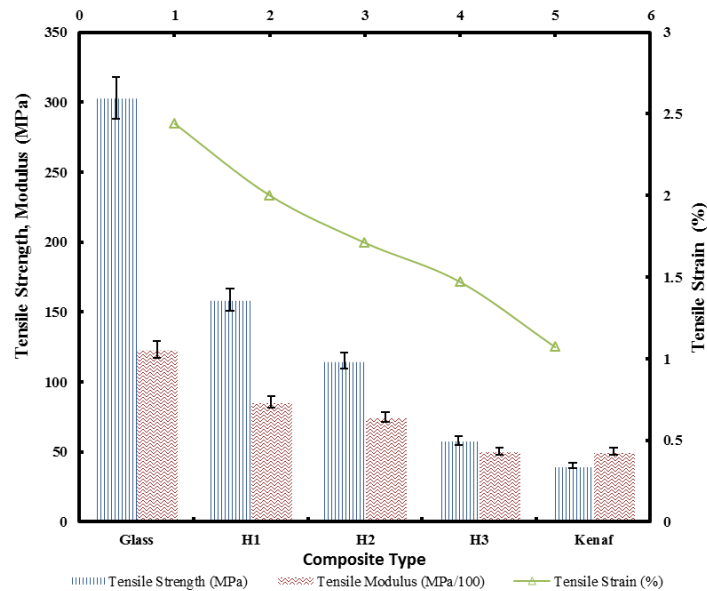


Fig. 3. Tensile strength, modulus, and elongation at break of composites

To determine the ultimate compressive strength, uniaxial compression tests were carried out for composites. Figure 4 presents the stress-strain curves of the materials, which show linear relationships for pure glass/UP and pure kenaf/UP composites, but non-linear behavior for hybrid composites. This behavior can be attributed to the differences in compressive strain between glass composite of 0.58% and kenaf composite of 1.32%. Woven kenaf/UP achieved an impressive ultimate compressive strength of 88 MPa. There have been limited studies reporting the compressive properties of natural kenaf, and there has been no scholarly work yet attempting a kenaf compression test with which to compare the results. Shah *et al.* (2013) studied the compressive strength of hemp natural fiber reinforced UP and reported a compressive strength of 95 MPa.

The compression results showed different trends than the tensile results and revealed the negative effect of hybridization. However, H1 showed an improvement of more than 10% in compressive strength compared with the kenaf/UP composite, with a weight reduction of 15% when compared with the glass/UP composite. In terms of failure mechanism, the glass, H1, and H2 composites failed in two stages of failure. The first mode was a linear deformation until a point near the ultimate stress. Then, the stress started to fluctuate within the ultimate strength limits for a short time before complete failure. The reason for this behavior is the difference in compressive strain of glass and kenaf fiber; in other words, the kenaf ply failed at this point and made an internal crack in the specimen, but transferred the load to glass plies. This justified the fluctuating load. Moreover, H1 and H2 composites followed a failure trend similar to that of glass composites because of their

high glass contents, 70% and 55%, respectively, whereas the H3 composites had only 30% glass. On other hand, H3 and kenaf showed similar behavior throughout the test, with a primarily ductile failure mode because of the high content of kenaf, which has higher compressive strain than glass.

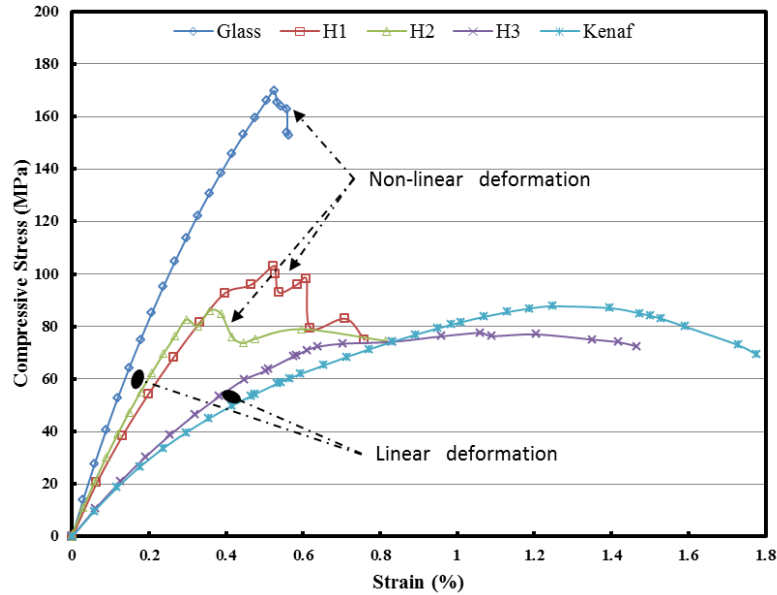


Fig. 4. Compressive stress-strain curves

Figure 5 shows the compressive properties of hybrid composites evaluated in this study and their corresponding strain values. Composite type H1 offered the best performance in terms of compressive strength and modulus, while possessing lower strain compared with other composites. Compression strength and modulus are important design parameters because composites are frequently used in flexure and the lower compressive strength will lead to high bending and instant failure (Piggott and Harris 1981). This resulted in a lower strain at break compared with other hybrid composites. The results confirm that H1 is good candidate for structural applications.

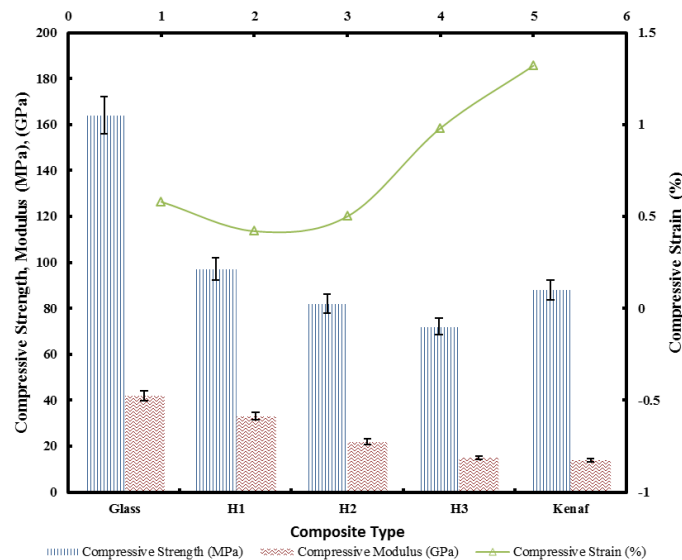


Fig. 5. Compressive strength, modulus, and strain results of composites

The flexural properties of glass reinforced UP, glass/kenaf hybrid composites, and kenaf reinforced UP are displayed in Figs. 6 and 7. Glass fiber composites show an expected superior flexural strength and modulus of 409 MPa and 17 GPa, respectively. Compared with glass composites, the flexural properties of hybrid composites show a smaller reduction rate than tensile properties and compression properties with replacement by kenaf. The flexural strength and flexural modulus of (H1) composite decreased by 33% and 4% respectively. The displacement was reduced up to 40% by replacing 30% glass with woven kenaf, while substituting of 45% of glass by kenaf reduced the flexural strength and modulus by 48% and 10% respectively. Compared with the kenaf composite, adding 30% glass to kenaf increased the flexural strength and modulus by 87% and 97%, respectively.

Figure 6 presents non-linear flexural stress-strain curves for all composites except kenaf composites; this non-linearity is similar to the compressive stress-strain of composites. It is well known that a specimen under flexural loading will be under combined load, with the top face under compression while the bottom face is under tensile loading (Yousif *et al.* 2012). A symmetric sandwich configuration (glass as shell and kenaf as core) was used in this work; thus, more glass content led to higher flexural strength. The stress increased at a constant rate until the point of fluctuation, when kenaf ply reached the maximum stress; failing caused a drop in stress value. The stress fluctuation in glass composites is due to the failure of internal plies because of the different tensile and compressive strength of composites.

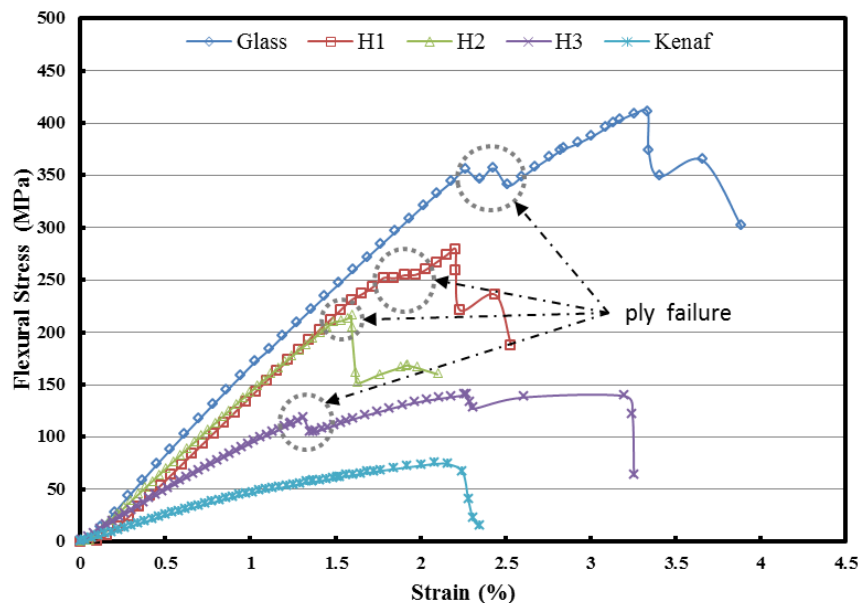


Fig. 6. Flexural stress-strain curves

The hybridization of natural fibers (as a core) and synthetic fibers (as a shell) in a sandwich configuration offers a noticeable improvement in flexural properties; this can be explained by outer layers controlling the flexural properties of composites (Khan *et al.* 2013; Yahaya *et al.* 2014).

Furthermore, the best weight ratio of kenaf to glass in fiber composites was 30%, which possesses the best properties under various loading conditions. This conclusion is supported by the results of Rao *et al.* (2009). Figure 8 shows an overall correlation for the

effect of kenaf replacement on density, tensile, compressive, and flexural strength of composites studied in this work; this guideline can be used to predict the properties of kenaf-glass hybrid composites according to fiber weight ratios for both fibers.

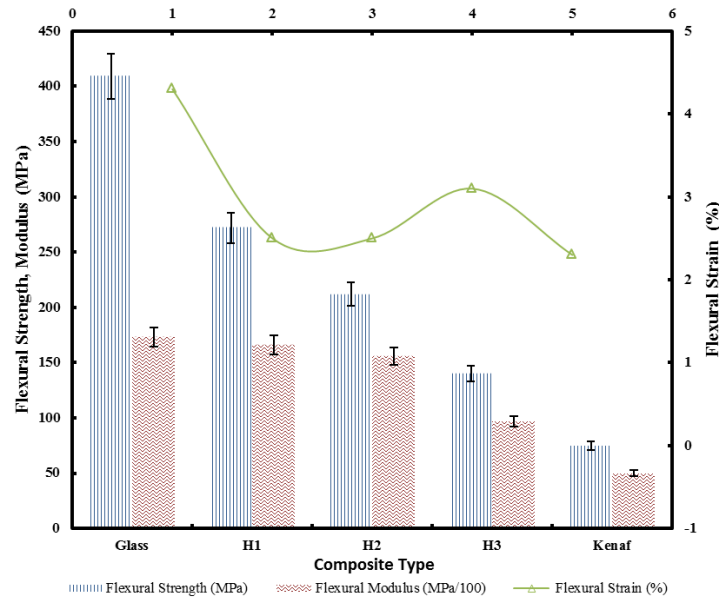


Fig. 7. Flexural strength, modulus, and strain results of composites

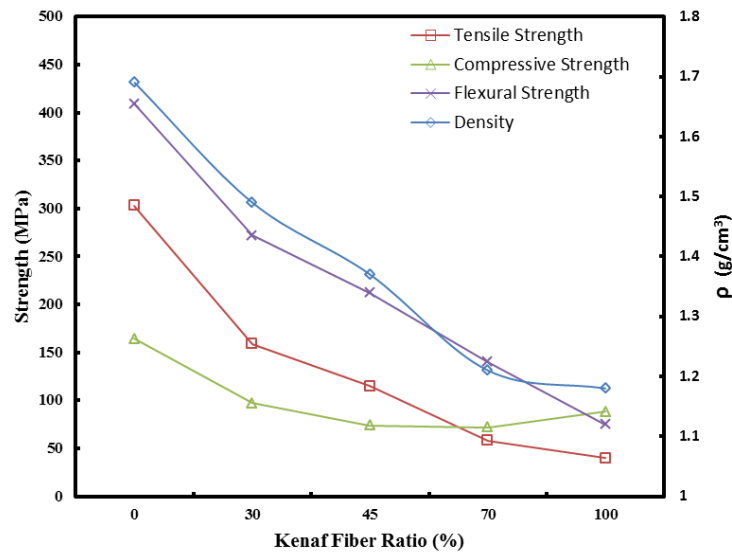


Fig. 8. The effect of kenaf fiber ratio on the density, tensile, compressive, and flexural strength of hybrid composites

Fatigue

According to the tensile test results, the ultimate tensile strength (UTS) of composites was used to determine fatigue stress levels for each composite. Four stress levels of UTS were used to plot the S-N curve, with three replications for each stress level, as shown in Fig. 9. The fatigue test stopped when 1 million cycles were reached or complete failure occurred. The experimental results in the Wohler diagram were fitted with a linear regression (Eq. 3) with R² value higher than 94%. Primary observations showed that the value of maximum fatigue stress was laid in descending order following their ultimate

static strengths starting from H1 to kenaf composites, which follows the rule of hybrid mixtures (Swolfs *et al.* 2014). On the other hand, the slope of the regression line was less steep as the kenaf fiber ratio increased; this can be attributed to the low crack propagation and low fatigue sensitivity of natural fibers (Shah *et al.* 2013).

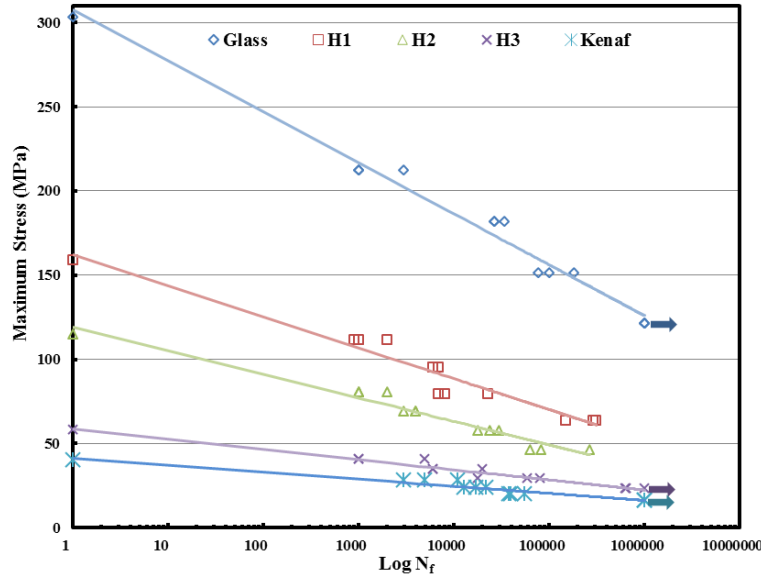


Fig. 9. S-N curves for composites fitted by linear regression. The arrowheads indicate that these samples survived 1 million cycles.

To establish a comparison that highlights the slight difference in fatigue sensitivity of composites, normalized S-N curves were plotted, as shown in Fig. 10. Stiffness degradation per decade is displayed in the diagram. The hybridization of fibers showed non-linear effects on the fatigue coefficient of hybrid composites, which is dissimilar to its effect on previous properties; these offer a linear relationship matching the rule of hybrid mixtures. H1 and H2 composites possess high sensitivities of 5% and 5.3%, respectively, compared with H3, although they have higher glass fiber content that has a low fatigue sensitivity of 4.5%. The reason for these behaviors might be the low stiffness degradation of kenaf fiber in the early stages of its life compared with glass composites, as illustrated in Fig. 11. Thus, H3 follows the rule of hybrid mixtures as H1 and H2 present non-linear relation of hybridization effect on fatigue sensitivity. In other words, the rule of mixtures is not applicable in fatigue life assessment; this conclusion is confirmed by Swolfs *et al.* (2014).

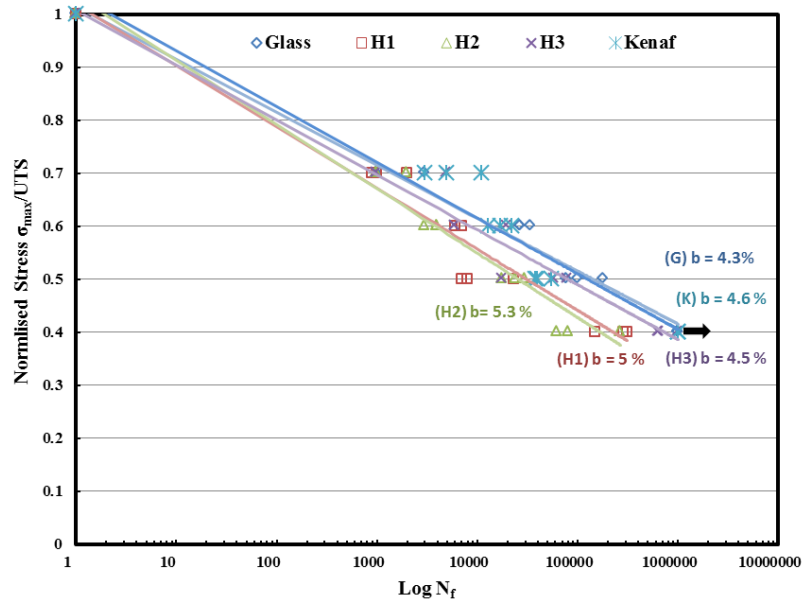


Fig. 10. Normalized S-N curves of composites showing the fatigue sensitivity coefficient (b)

Figure 11 was divided into three zones according to the degradation trends of composites. The first zone presents maximum loss of stiffness because of matrix crack initiation, which commonly occurs with brittle composites. Kenaf composites showed the lowest degradation rate, with only 10% stiffness, while glass composites were reduced by 30%. The second zone showed an almost constant slope for modulus loss and began to increase in the third zone before failure. Therefore, it was found kenaf and hybrid composites with high kenaf ratio, that their stiffness's degraded at a lower rate compared to glass composites; these observations were confirmed and well documented from studies of the fatigue life of woven hemp composites by de Vasconcellos *et al.* (2014) and Shah *et al.* (2013).

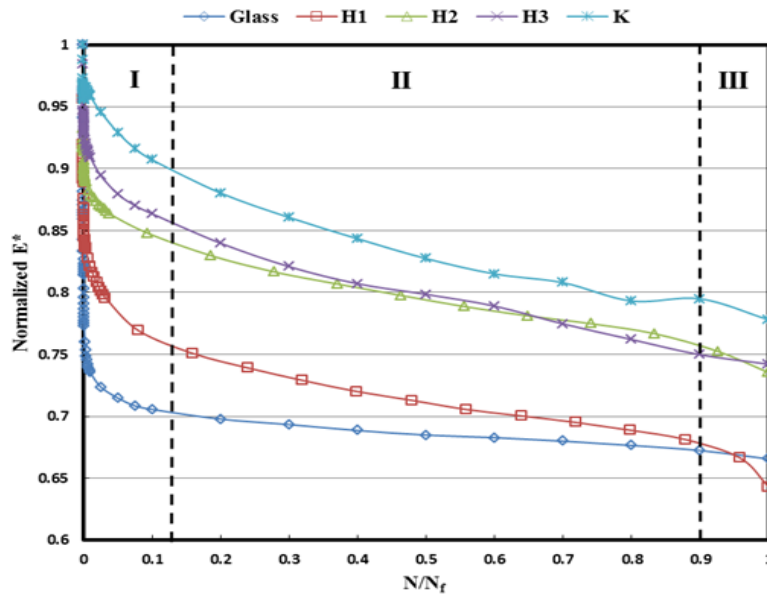


Fig. 11. Normalized dynamic modulus-cycle of composites during fatigue loading at 40% of UTS

Failure modes in tensile fatigue loading were similar to those in monotonic loading, which shows a brittle catastrophic failure with large-scale delamination. The fracture of kenaf plies was clean, with few bundles pulled out; glass shows more fiber pulled out as well as fiber breakage. This is an indication of high load resistance and also due to different strain at break value for fibers, which is quite common in sandwich composite configurations (Shahzad 2011; Bagheri *et al.* 2013; Sharba *et al.* 2016a).

Figure 12 illustrates the temperature changes of composites during fatigue loading. The temperature of a specimen changes because of friction and loss of stiffness within the elastic zone or low cyclic fatigue regime; after certain number of cycles the temperature will remain constant, the time needed to reach stabilizing point of temperature depends on the type of fiber, fiber orientation, and maximum stress applied, as these parameters affect damage propagation. In the literature, it was reported that 7×10^3 cycles is enough for temperature stabilizing (Bagheri *et al.* 2014); another study used a block of 10^4 cycles, which showed stable temperatures (Montesano *et al.* 2015). The heat was monitored for the first 10^4 cycles and the change in ambient temperature was recorded and plotted in Fig. 12. The heat generated kept rising until 7000 cycles; after that, it stabilized. This is related to the stiffness degradation of composites in the first zone in Fig. 11. Generally, heat generated because of the internal friction of composites was within the acceptable range recommended in the literature (Gassan and Dietz 2003; Harris 2003).

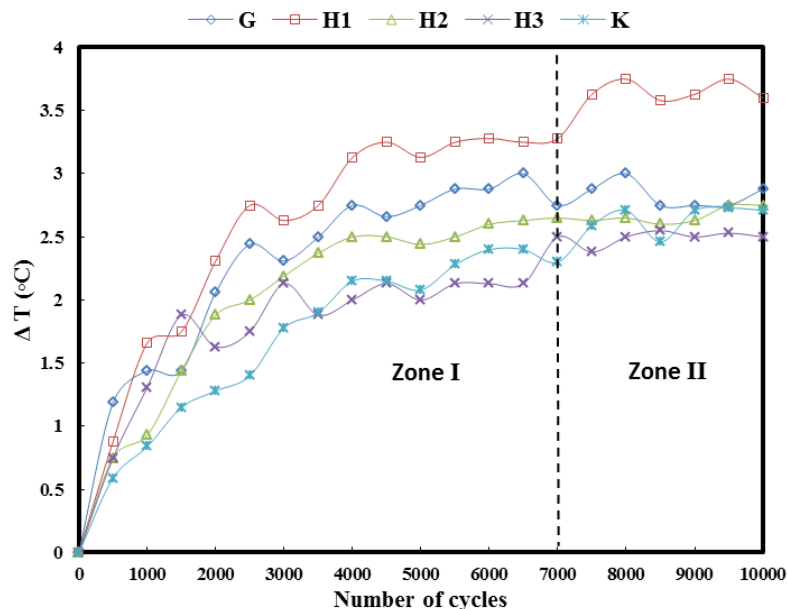


Fig. 12. Change in composites' surface temperature during fatigue loading

Morphological Properties

The tensile and compression failure sections of kenaf /UP and H1 composites were examined using a SEM to get a closer view of the adhesion of woven kenaf with the matrix and hybrid composites and the fracture modes of hybrid composites with various loading conditions. Figure 13(A-D) shows the tensile fracture section of kenaf reinforced UP; the kenaf fiber showed a good adhesion with the matrix because of the elimination of the moisture content of kenaf. The highest scale failure mode is fiber breakage with a few bundles pull out. This indicates good fiber-matrix bonding. The failure sequence observed started with a matrix crack that held the initial load because of the low elongation. Then,

the matrix started to debond and transfer the load to fibers, which resulted in the final mode of fiber breakage and complete failure.

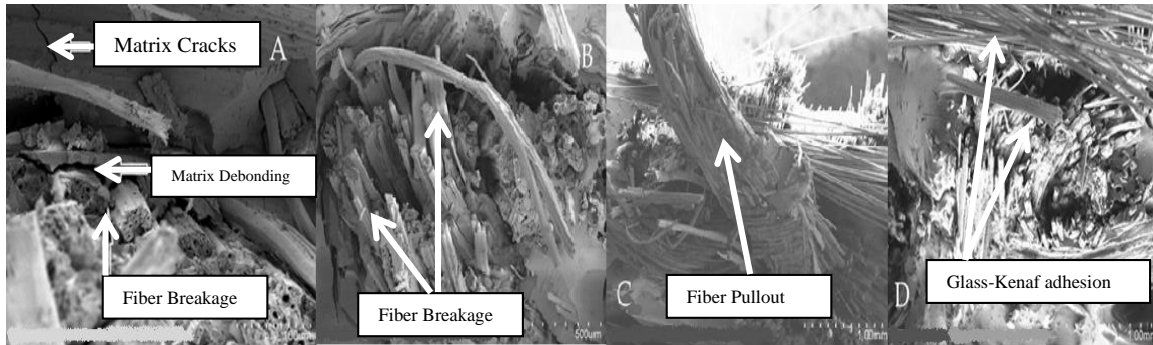


Fig. 13. Tensile failure surfaces of (A, B) kenaf and (C, D) H1 composites

Figure 14 (E-H) presents the fracture surfaces of kenaf /UP and H1 composites with compression loading. A small area of delamination between glass and kenaf at a specific load value was noticed without failure. That point presents maximum stress for kenaf; therefore, the load was carried by glass shell plies until final failure occurred. This can be explained by the difference in elongation at break, as well as the ultimate strength of kenaf and glass and can also explain the nonlinear behavior shown in Fig. 7. Most specimens undergo sudden failure after ultimate compressive strength is reached. The small scale of delamination indicates a good adhesion between glass and woven kenaf.

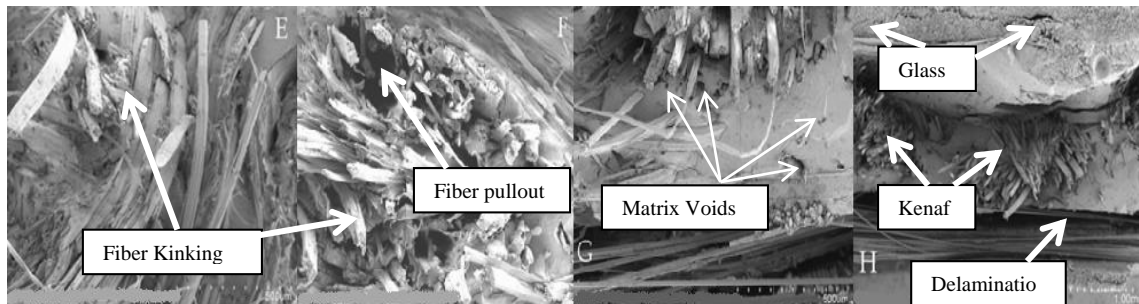


Fig. 14. Compression fracture surfaces of (E, F) kenaf/UP and (G, H) H1 composites

CONCLUSIONS

1. The composites in this work followed the rule of hybrid mixtures in terms of monotonic tensile and flexural properties.
2. There was no major effect of hybridization on the compressive properties of composites, except a slight improvement for H1 hybrid composites when compared with kenaf and other hybrid composites.
3. The best hybridization weight ratio of kenaf to glass was 30:70; these composites had the highest set of monotonic properties at each loading condition and showed a great balance of mechanical properties between kenaf and glass composites.

4. Hybridization of fibers had a non-linear effect on the fatigue coefficient of hybrid composites; H3 composites had the best fatigue performance, with lower stiffness degradation than glass and other hybrid composites.
5. Surface heat during fatigue loading condition is another indication of stiffness loss in hybrid composites.
6. The morphological study revealed good adhesion and compatibility between woven kenaf and glass reinforced unsaturated polyester, which displayed high dimensional stability and load transfer in hybrid composites under various loading conditions and confirmed the suitability of natural fibers in structural applications.

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