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Flexural and fatigue behaviour of natural fibrous reinforced polymeric composite materials

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A R T I C L E I N F O

A B S T R A C T

In this study, the mechanical properties, fatigue life, and endurance limit values were investigated for composite materials containing natural fiber reinforcement (flax, wool), which were arranged by 0°/90° Angle orientation and a combination of 0°/90° and 45°/-45° angle orientation, then the wool woven mixed by flax woven and unidirectional flax interfered with jute woven. Binary blends containing epoxy and polyurethane at v were mixed at various weight percent (0%, 5%, 10%, and 15 %) vacuum infusion technique was used to prepare the specimens. ANSYS Workbench was used as numerical software to investigate the fatigue behavior and endurance limit values of the unreinforced and reinforced blend. It was found that the weight percentage of 10% polyurethane in the blends was the optimal percentage providing the best fatigue life and the endurance limit value, endurance limit values of wool composite improved when hybridized by flax woven and unidirectional flax interfered with jute woven by 132.895 % and 66.549 % respectively.

1. Introduction

The composite material consists of two or more constituent materials insoluble in each other: the matrix (continuous phase) and the reinforcement [1].

The growth using synthetic materials in industry applications increased environmental problems because these materials are not environmentally friendly, natural fibers offered an alternative to replace synthetic fibers, and these bio-material fibers have great potential as reinforcements, which provide thermal stability, low cost, lower energy requirement, wide availability, excellent biodegradability and environmentally friendly [2, 3]. The fatigue phenomenon is the cause of most fractures in engineering parts during service with the presence of cyclic loads, the fracture occurs under withstanding loads, which are still within the elastic zone under the stress-

strain curve. At service, fatigue failures are involved in at least 90% of all mechanical failures. For brittle materials, fatigue failures are particularly dangerous because they do not usually show signs of imminent failure, but this happens suddenly and without noticing the overall plastic deformations, which throughout history have caused important accidents with catastrophic consequences [4, 5].

Abdullah, A. H., et al. investigated the tensile and fatigue behavior of epoxy reinforced with unidirectional kenaf. The results were compared with unreinforced epoxy, which showed that increasing the volume fraction of kenaf improved the fatigue life [6].

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Nomenclature:

EP	epoxy	*symbols*	
Pu	polyurethane	Fa	flax laminate arranged by 0°/90° angle orientation
Pu5	The blend contains 95% epoxy and 5% polyurethane	Fb	flax laminate arranged by a combination of 0°/90° and 45°/-45° angle orientation
Pu10	The blend contains 90% epoxy and 10% polyurethane	Wa	wool laminate arranged by 0°/90° angle orientation
Pu15	the blend contains 85% epoxy and 15% polyurethane	Wb	wool laminate arranged by a combination of 0°/90° and 45°/-45° angle orientation
JF	unidirectional flax interfered with jute woven	Hwaf	hybrid contains wool and flax

unsaturated polyester resin as a base material supported with natural wool fibers, which were distributed randomly, with weight fractions (3%, 4%, and 5%). The results of the research showed that the value of the impact resistance and electrical insulation increased with increasing the weight of the wool fiber [7]. Bensadoun, F., et al. investigated the fatigue behavior of composite material made by epoxy reinforced with five architectures textile fabric of the flax, which are random mat, plain weave,

twill, quasi- unidirectional, and unidirectional with a volume fraction of 40%, except 30% for the mat. The result showed that the fatigue behavior was affected by changing the type of architectures flax fabric type, minimum fatigue life for the random mat fabric, the fatigue life was increased for plain weave and twill fabric, and the highest at using the quasi- unidirectional fabric [8].

Hojo, T., et al. fabricated and tested polymeric composite containing several types of a mat natural fiber, which included unidirectional jute, unidirectional kenaf, and unidirectional bamboo, unsaturated polyester was used as a matrix. The test included tensile and low cycle fatigue. The results were compared with a unidirectional glass mat. The result showed that natural fibers show good properties as reinforcement into composites compared with Glass fiber and show a potential replacement with some types of synthetic fiber [9].

Asgarinia, S., et al. investigated the fatigue the behavior of composites material made by epoxy reinforced with flax (F) as natural fiber woven and E-glass (G) as synthetic woven, the vacuum infusion was used to fabricate the samples several cycles- stress to failure (S-N) of all hybrid configurations were obtained. By comparison between flax and glass hybrid, the flax composites have good fatigue behavior, which shows a potential implementation in bearing applications [10].

2 Experimental works

2.1. Matrix material

The epoxies polymerase has good mechanical properties, but they have low break deformation, low crack propagation resistance, and is brittle. In contrast, the polyurethane polymer has low mechanical properties, flexible and elastic. Depending on the mixing weight percentages ratio between epoxy and polyurethane, epoxies' disadvantages can be reduced.

The blend is prepared by mixing the epoxy (Ep) and the polyurethane (Pu) (at 0 %, 5 %, 10 %, and 15 % weight percentages), which are blended by the following steps (Figure 1a): 1- the epoxy and polyurethane resins were mixed by the requiring weight percentage. 2- The epoxy and polyurethane hardeners were mixed by the required weight percentage. 3- All the components of the resins and hardeners were mixed. 4- A vacuum chamber was used to remove the bubbles from the components.

2.2. Natural fiber reinforcements

Three types were woven (Figure 1b) used to reinforce the matrix, which: are flax, wool, and unidirectional flax interfered with jute woven (Jf).
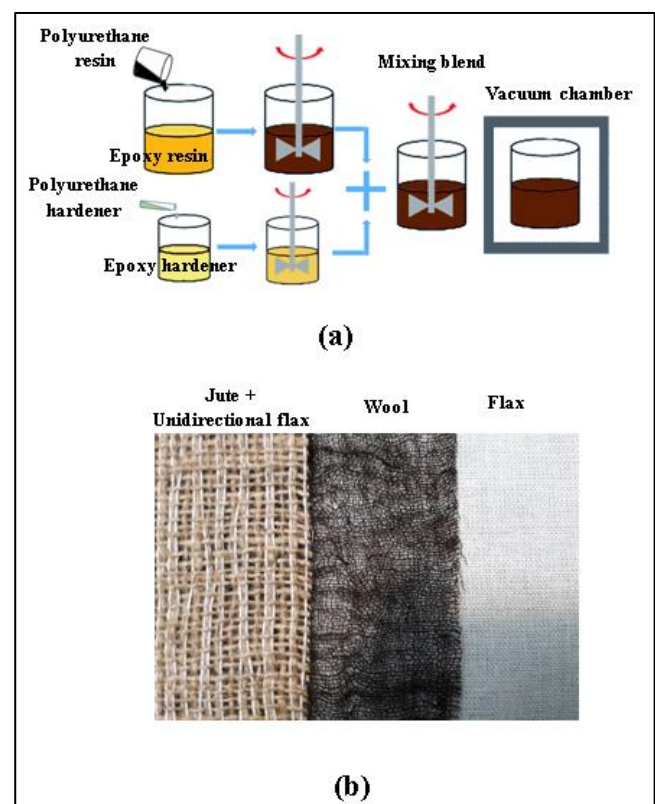
Figure 1. Preparation, (a) Mixing blend, (b) Natural fiber reinforcements

2.3. Fabrication of composite materials

The vacuum infusion technique was used to prepare the specimens, Figure 2 shows the equipment used in the system, which is; a vacuum pump, vacuum chamber, trap, digital weighing scale, pressure gauge, and woven fibers stacked within a vacuum bag, this bag must be completely hermetic with its respective input and output blend pipelines, and then the vacuum pump was activated to extract the air and to check the leak. The pressure difference leads to infusion, which allows the blend to pass through the

woven fibers until saturation, then the inlet and outlet of blend tubes were closed, and the pump is turned off. The mold was kept for three days to cure at room temperature [11]. The wool layers are arranged by 0°/90° angle orientation (Wa) and a combination of 0°/90° and 45°/-45° Angle orientation (Wb), also the flax layers are arranged by 0°/90° angle orientation (Fa) and a combination of 0°/90° and 45°/-45° (Fb).

Figure 2. Vacuum infusion technique

To improve the mechanical properties of wool, the woven wool (Wa) was hybridized by two laminates at the top and two laminates at bottom of flax (HWaf), and the woven wool (Wa) was hybridized by one layer of Jf at the top and the other at the bottom (HWajf), as shown in Figure 3.

a

b

Figure 3. Hybrids composites

2.4. The mechanical properties

Flexural and fatigue life test was used to analyze the mechanical properties of the fabricated composite samples.

Bending test : Three-point bending (flexural tests) was applied according to ASTM D790 (Figure 4). The mechanical properties of the unreinforced and reinforced blend were measured. The bending tests were carried out using the universal machine Tinius Olsen h50kt with a maximum capacity of

50KN. The separation between supports was determined using a 16:1 span-to-thickness ratio [12]. The dimensions of the specimens were established by 125x10x4 mm (Figure 5) and span length = 64 mm, the test speed was 2mm/min at room temperature.
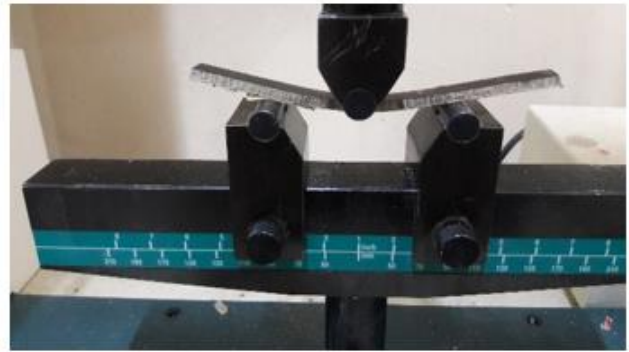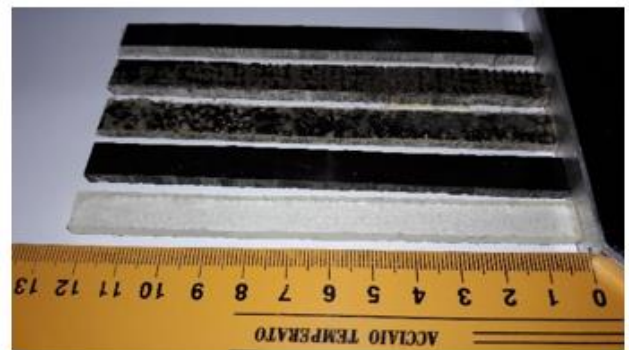

Figure 4. Bending testing machine

Figure 5. Bending specimens

Figure 6. Fatigue testing machine

Fatigue Test : Machine type HITECH (HSM-20) with alternative bending stress was used to test the fatigue life at constant amplitude (Figure 6). The specimens were fixed at one end, while the alternative bending stress was subjected to the other end. The dimensions of the specimens were established by 100x10x4 mm (Figure 7).

Figure 7. Fatigue specimens

Figure 9. Numerical fatigue of the specimens

The stress value (σ), determined by the specimen deflection (δ_e) and the specimen's effective length (l_e), which is calculated by applying the relation [13].

$$\sigma = \frac{1.5 E_f t \delta_e}{l_e^2} \qquad (1)$$

Where,

σ: is the alternative bending stress (MPa)

E_f: the flexural modulus (MPa)

t : is the thickness of the specimens (4 mm)

δ_e : is the deflection of the specimen (mm)

l_e : is the specimen's effective length (mm)

3. Numerical analysis

ANSYS.19 Workbench was used as numerical software to investigate the fatigue results of unreinforced and reinforced composite. In this work, hex dominant was used to carry out element type, the number of elements was 2400, and the number of nodes was12389, as shown in Figure 8. The boundary conditions of the model applied are fixed support on the first side and the alternative load effect on the other side. The material properties were imported from the experimental results [14].
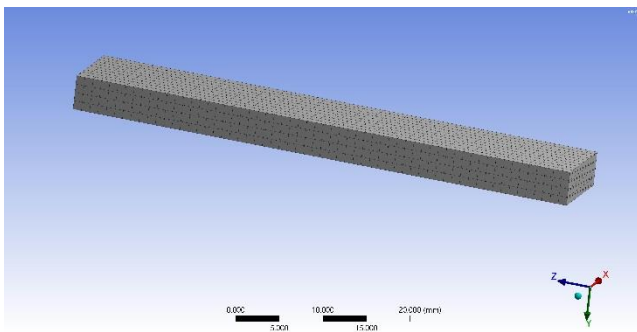

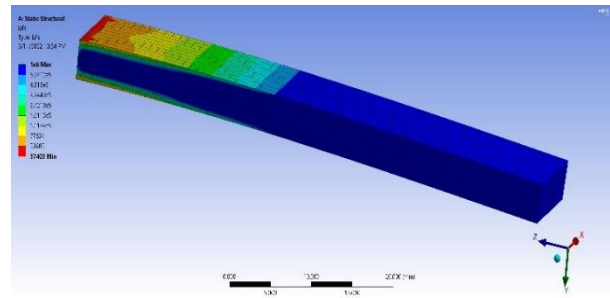**Figure 8. The meshing of the specimens**

4. Results and discussion

4.1. Bending Results

Figure 10 shows the Stress-Strain curves of the blend matrix which is mixed into the blend by (0%, 5%, 10%, and 15% Pu). The samples were tested without natural fiber reinforcement and the results are shown in Figure 11, which include the yield stress, ultimate stress, and maximum strain.
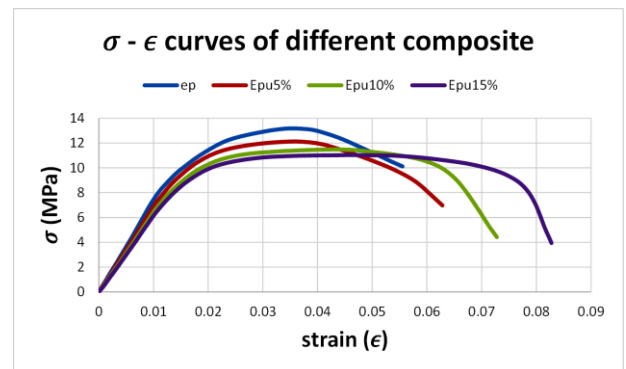

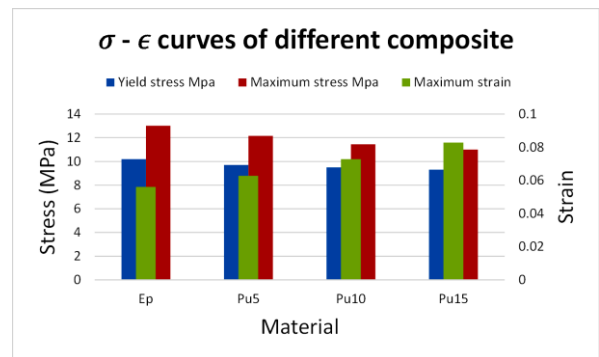**Figure 10. Stress-strain curves of different composite materials**

Figure 11. Stress-strain curves result from different composite materials

Compared with pure epoxy, mixing polyurethane with epoxy reduces the yield stress and ultimate stress while increasing the maximum strain.

Figures 12, 13, and 14 show the Stress-Strain curves of wool woven composites, flax woven composites, and the hybrids respectively, the results of these tests are shown in Figure 15.
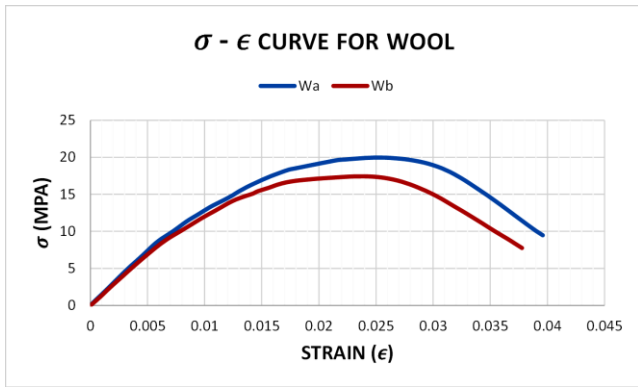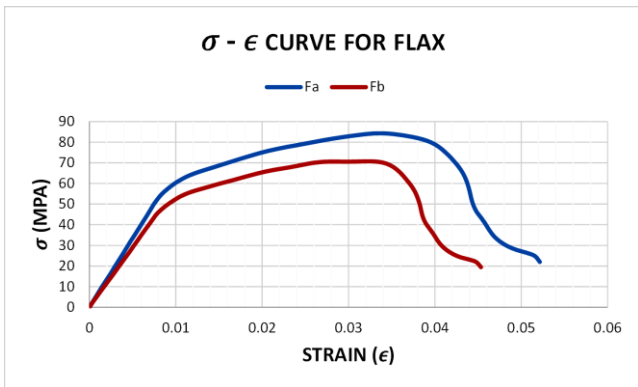

Figure 12. Stress-strain curves of Wa and Wb

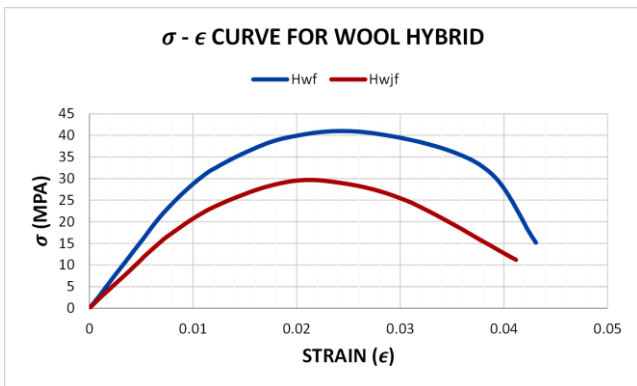**Figure 13. Stress-strain curves of Fa and Fb**

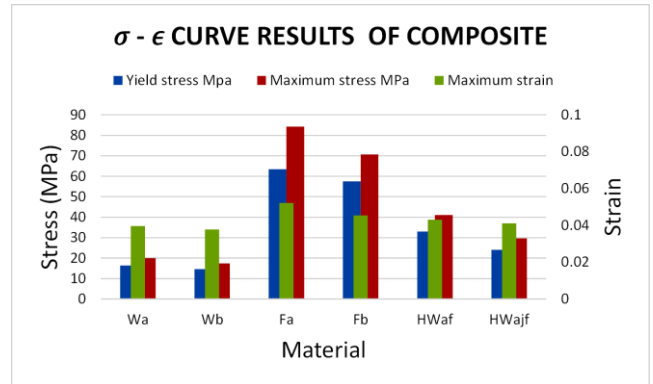**Figure 14. Stress-strain curves of the hybrids**

Figure 15. Stress-strain curves result from the composites

Comparison of the results between the wool woven and flax woven composites arranged by 0°/90° angle orientation and a combination of 0°/90° and 45°/-45° Angle orientation, respectively, showed that the yield stress was higher by 10.976 % and 9.306 %, while, the max strain was higher by 4.599 % and 13.069 %.

Comparison results between hybrids (HWaf and HWajf) and Wa showed that the yield stress was increased by 101.219 % and 46.951 %, respectively, while, the maximum strain increased by 8.81 % and 3.953 %.

4.2. Fatigue Results

The stress fluctuated between maximum stress (σ_{max}) and minimum stress (σ_{min})

The stress ratio $R = \frac{\sigma_{min}}{\sigma_{max}}$ (2)

For fully reverse stress: $\sigma_{max} = -\sigma_{min}$ and for static stress: $\sigma_{max} = \sigma_{min}$ [15]. The specimens of the fatigue tests were examined at fully reverse stress (R = -1), which was applied to the samples to investigate the number of cycles to fatigue failure.

The S-N curve was obtained by testing a number of the specimens, which were subjected to a specific value of stress. Starting with a high-stress value (less than the yield stress), the number of cycles (N) until rupture was counted. This procedure was repeated gradually by decreasing the value of the stress and counting the number of cycles for each test. Figures (12, 13, 14, and 15) show S-N curves of fatigue tests for blends, wool woven composites, flax woven composites, and hybrids. All tests stopped when the number of cycles reached 10^6 cycles
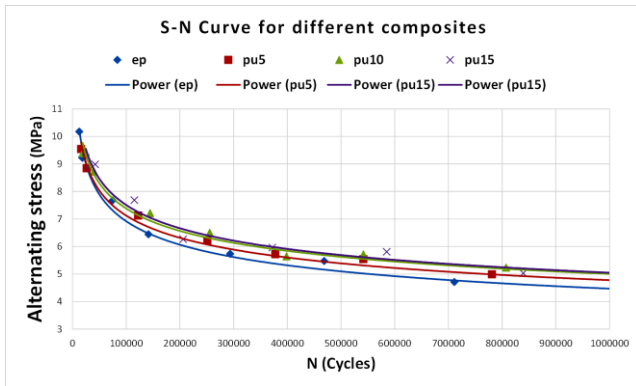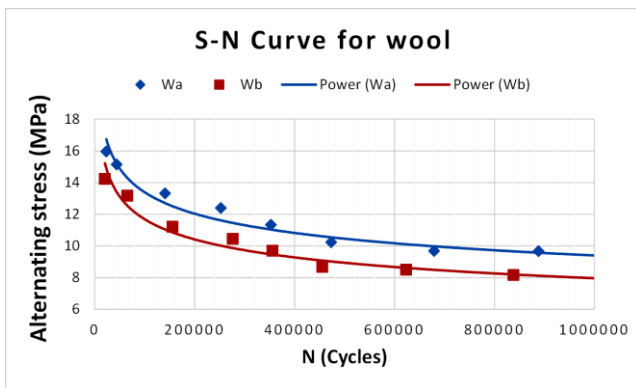
Figure 16. S-N curve of different composites

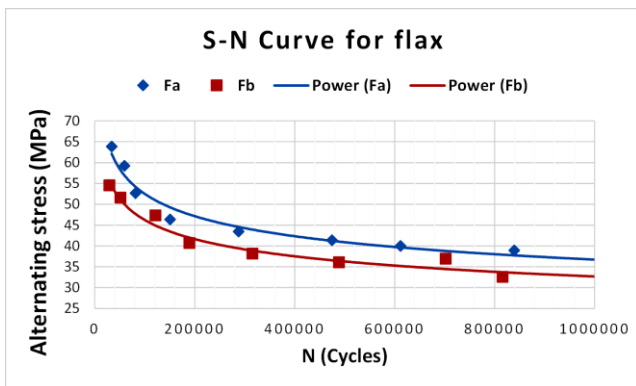
Figure 17. S-N curve of the wool composites

Figure 18. S-N curve of the flax composites

The S-N curve was modeled using the parametric relationship known as Basquin's law [64], which represents the relation between the stress and the number of cycles (N) until rupture on an S-N curve. There is no stress limit in the S-N curve for non-ferrous material, such as composite material. In these cases, the S-N curve is reached in a certain number of cycles (10^6 cycles), which is called the endurance limit (σ_e) [16, 17].

$$\sigma = A_1 N^{\beta} \tag{3}$$

Where: σ is the stress, N is the number of cycles until rupture, A_1 and β are the adjustment coefficients characteristic of the material and the test conditions.
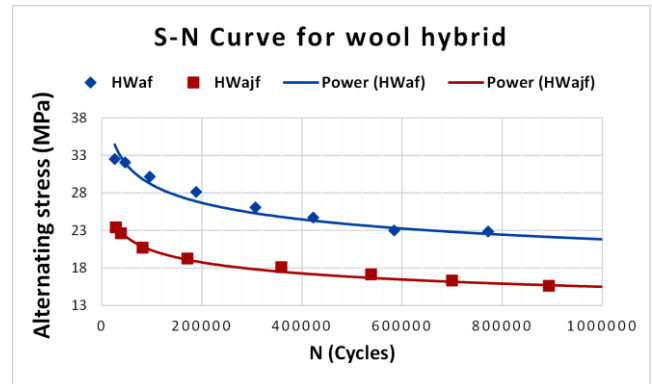

Figure 19. S-N curve of the hybrids

The fatigue tests results of the blends and the composites are shown in Table 3 and Table 4 respectively, including the experimental S-N curve equations, the regression (R^2), ANSYS S-N curve equations, the endurance limit (σ_e) value at 10^6 cycles for the experimental and ANSYS results and the Errors between them. Comparing the experimental value of endurance limit (σ_e) between the pure epoxy with 5%, 10% and 15% of polyurethane blends, the endurance limit increased by 6.452 %, 12.061 %, and 12.421 % respectively.

For the composites, Wa has a higher endurance limit value by 15.174 % than Wb and Fa has a higher endurance limit value than Fb by 11.632 %. HWaf and HWajf have higher endurance limit values than Wa by 132.895 % and 66.549 % respectively

5. Conclusions

The main conclusions were withdrawn as follows:
1. Mixing the polyurethane with epoxy decreased the yield stress and maximum stress while increasing the maximum strain.
2. The composites consisting of fiber arranged by 0°/90° have mechanical properties (yield stress, ultimate stress, and maximum strain) higher than composites consisting of fiber arranged by a combination including 0°/90° and 45°/-45°.
3. The mechanical properties of Wa were improved at hybridization by Fa and jute (HWaf and HWajf).
4. For blends, the endurance limit value and fatigue life improved by increasing the polyurethane percentages in the blends to a until10% percentage.
5. The composites consisting of fiber arranged by 0°/90° have endurance limit value and fatigue life higher than composites consisting of fiber arranged by a combination including 0°/90° and 45°/-45°.
6. The endurance limit value and fatigue life of Wa were increased at the hybridization with Fa and jute.

Table 1. The fatigue tests results of the blends

Samples	S-N curve equations			Fatigue strength at 10^6 cycles (MPa)		
	Experiment	R²	ANSYS	Experiment	ANSYS	Errors%
Ep	$\sigma = 61.569N^{-0.19}$	0.9829	$\sigma = 60.59N^{-0.193}$	4.4603	4.2112	5.9159
Pu5	$\sigma = 52.543N^{-0.174}$	0.9793	$\sigma = 55.521N^{-0.182}$	4.7480	4.4922	5.6958
Pu10	$\sigma = 51.62N^{-0.169}$	0.9784	$\sigma = 57.563N^{-0.181}$	4.9983	4.7223	5.8442
Pu15	$\sigma = 54.728N^{-0.173}$	0.9729	$\sigma = 60.58N^{-0.184}$	5.0143	4.7679	5.1672

Table 2. The fatigue tests results of the composites

Sample	S-N curve equations			Fatigue strength at 10^6 cycles (MPa)		
	Experiment	R²	ANSYS	Experiment	ANSYS	Errors%
Wa	$\sigma = 78.551 N^{-0.154}$	0.9616	$\sigma = 81.86 N^{-0.159}$	9.3573	9.1006	2.8206
Wb	$\sigma = 79.741 N^{-0.167}$	0.9588	$\sigma = 82.173 N^{-0.171}$	7.9375	7.7398	2.5540
Fa	$\sigma = 313.56 N^{-0.155}$	0.9718	$\sigma = 332.64 N^{-0.163}$	36.8401	34.9925	5.2801
Fb	$\sigma = 262.19 N^{-0.151}$	0.9640	$\sigma = 318.42 N^{-0.169}$	32.5549	30.8319	5.5883
HWaf	$\sigma = 122.55 N^{-0.125}$	0.9411	$\sigma = 128.46 N^{-0.131}$	21.7928	21.0265	3.6443
HWajf	$\sigma = 79.56 N^{-0.118}$	0.9760	$\sigma = 85.245 N^{-0.127}$	15.5846	14.7458	5.6880

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