Kerbala Journal for Engineering Science
https://kjes.uokerbala.edu.iq/

Evaluating the Fatigue and Flexural Properties of Natural Fibers Reinforced Blend Matrix Composites

Ali M. Jasim [a]*, Ibtihal A. Mahmood [a]

[a] Mechanical Engineering Department, University of Technology, Baghdad, Iraq.
* Corresponding author, Email: alimohjasim@gmail.com

Received: 24 July 2022; Revised: 27 October 2022; Accepted: 29 December 2022; Published: 31 December 2022

Abstract

Natural fibers have economic and environmental advantages, offering attractive alternatives for different applications such as automotive parts, door inserts, dashboards, seats, etc. In this research, the flexural properties (using 3 point bending test), S-N curve and endurance limit values were evaluated for composite materials. The blend contains 90% epoxy and 10% polyurethane by the weight fraction was used as matrix, cotton, jute and silk natural woven fibers were used as reinforcement, which was laminated by 0/90 and by a combination of 0/90 and 45/-45 Angle orientation for each type reinforcement. Then, the cotton layers were hybridized by three types of arrangement, which include: cross interfering between jute woven and unidirectional flax fiber as interplay (JF) woven (HCajf), short fibers of jute and silk distributed randomly (HCajs) and silk woven (HCas). A vacuum infusion system (VIS) was used to prepare the sample. SEM was used to investigate the characterization of microscopy images. The evaluated results showed that the mechanical properties, fatigue life and endurance limit value of a composite laminated with 0/90 Angle orientation is higher than the composites laminated by a combination arrangement of 0/90 and 45/-45 Angle orientation. Hybridization of the cotton composites by three-type arrangement (HCajf, HCajs and HCas) improved the mechanical properties, fatigue life and endurance limit increased by 38.229 %, 21.017 % and 6.303 %, respectively, the hybridization with natural silk fiber has a significant effect on the mechanical properties and ductility of the composite material. SEM tests for fatigue samples detected several types of damage mechanisms related together, which caused degradations growing on different scales.

Keywords: Composite materials, Fatigue life, Flexural tests, SEM tests, Natural fiber.

1. Introduction

Industrial applications need a rigid materials combination, mechanical resistance, high toughness and lightness. The traditional material can't combine these characteristics to achieve this goal. It is necessary to use composite material. Composite materials are gathered of different materials with significantly different properties that union produces better properties than individual constituents [1, 2].

Using synthetic materials (such as fiberglass and carbon) in the composite increased the environmental problems as these materials are not environmentally friendly and non-biodegradable. Natural fiber offers a replacement based on an environmentally friendly, produced from a renewable resource, available in worldwide, biodegradable, non-toxic and low costs [3, 4].

Fundamentally, composite materials' properties are controlled by their constituents' properties, fibers orientation and fiber/matrix interface [2].

Combining two or more different types of reinforcement fibers in the same matrix produces hybrid composites. Mixing cheaper and lower quality fibers with higher quality fibers can improve the properties of the composite without affecting costs compared with non-hybrid composites or improve the disadvantages of one type of reinforcement fibers by adding other reinforcement types. Hybridisation can also improve fatigue behaviour [5, 6].

The phenomenon of fatigue is known as the deterioration that occurs in subjected elements at repeated loads. The fatigue failures occur in the element less than the static breaking stress and even at the elastic zone of the material. Fatigue causes more than 90% of machines' failures, and fracture in brittle materials is difficult to predict since it occurs suddenly, which can cause catastrophic accidents [7, 8].

Ranga et al. reviewed various types of natural fibers as reinforcement into the composite materials, which could explore for different applications. Natural fibers are offered high strength and low weight and are available naturally in abundant resources. Still, only a few researches have been investigated and used so far, so these renewable resources need to explore their full potential by using natural fibers to develop science and technology [9].

Rajasekar. prepared composite materials containing polyester as a matrix and jute are woven fabric as reinforcement. The mechanical properties were tested, and the experimental result was compared to the ANSYS software result. The experimental result was achieved to find an appropriate type of application for this product [10].

A. M. Hameed studied polymer matrix behaviour containing natural fibers as an alternative to glass fibers. Unsaturated Polyester was mixed with a reinforcement, including glass fiber, reed, palm and jute. The test results showed that Jute fibers had good properties of flexural and impact strength, with excellent thermal and acoustic insulated, compared with glass and other natural fibers [11].

Paudzi et al. investigated the fatigue life of hybrid material made by epoxy reinforced with a woven of kenaf and kevlar-29. The vacuum infusion method was used to fabricate the samples. The kenaf / kevlar-29/ epoxy results were compared with the kenaf/epoxy at different volumes fraction, showing improvement in fatigue life at low cycle fatigue [12].

In this research, the mechanical properties and fatigue behaviour of composite materials containing natural fibers (cotton, jute and silk woven) were studied, and the weakest composite material (containing cotton fibers) was hybridized to improve its properties and then examined the fracture surface using a SEM (Scanning Electron Microscopy) to analyze the damage mechanisms.

The objectives of this study were to investigate the fatigue life of natural fibers reinforced blend matrix subjected to bending cyclic stress and examine the fracture surface using a SEM (Scanning Electron Microscopy) to analyze the damage mechanisms.

2. Materials and Methods

2.1. Materials

The thermosetting blend was prepared by mixing the epoxy (Ep) by weight fraction 90% with polyurethane (Pu) 10% percentages. Polyurethane was used to increase the ductility of the blend.

The reinforcement woven, as shown in Figure 1, was used to manufacture the composite, which respectively includes:

1. Cotton
2. Jute
3. Silk
4. Hybridization cross interferes between Jute woven and unidirectional flax fiber as interplay (JF) because the mechanical properties and fatigue life of the composite containing flax fiber, are higher than that containing jute fiber [13].

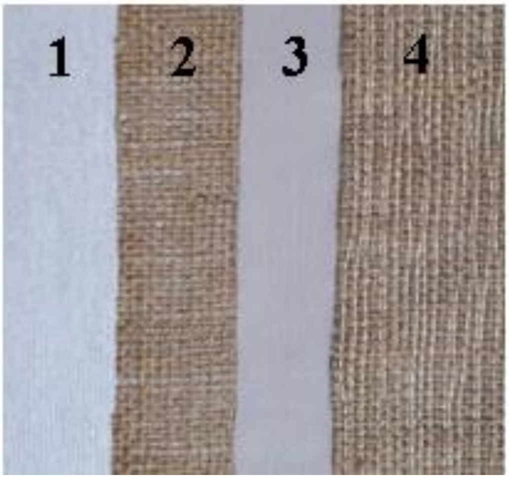

Figure 1 reinforcement woven.

2.2. Composite Preparation Process

A vacuum infusion system (VIS) was used to prepare the composite sample, providing low-cost laminates. Figure 2 shows the connections, materials and equipment, including the vacuum pump, digital scale weighing, pipeline, pressure gauge, trap and vacuum chamber.

The reinforcement fibers material was arranged on the mold, placed into a flexible bag and tightly enclosed. Once the vacuum is applied, the pressure and air inside the bag decrease. The pressure differences between vacuum pressure and atmospheric pressure allowed the blend to pass through the pipes, which impregnated the reinforcement fibers until saturation, the outlet and inlet of blend pipes closed, and the vacuum pump was turned off. The laminates were left 3 days to cure at room temperature [14].

2.3. Specimen Preparation

Firstly, the layers of the sample are sorted by six types of composite arrangement, which include:

The cotton (Ca), jute (Ja) and silk (Sa) layers were laminated by 0/90 Angle orientation, and cotton (Cb), jute (Jb) and silk (Sb) layers were laminated by a combination arrangement of 0/90 and 45/-45 Angle orientation. The weight fraction of the cotton, jute and silk was 52. 762 %, 48. 2727 % and 44.29 %, respectively.

Then, cotton layers were hybridized by three types of arrangement, which include:

a. Cotton (Ca) layers hybridized by JF layers (HCaJF) as shown in Figure 3 (a).

b. Cotton (Ca) layers hybridized by short jute and silk fibres randomly distributed at the middle (HCajs) as shown in Figure 3 (b).

c. Cotton (Ca) layers hybridized by silk (Sa) layers (HCaSa) as shown in Figure 3 (c).

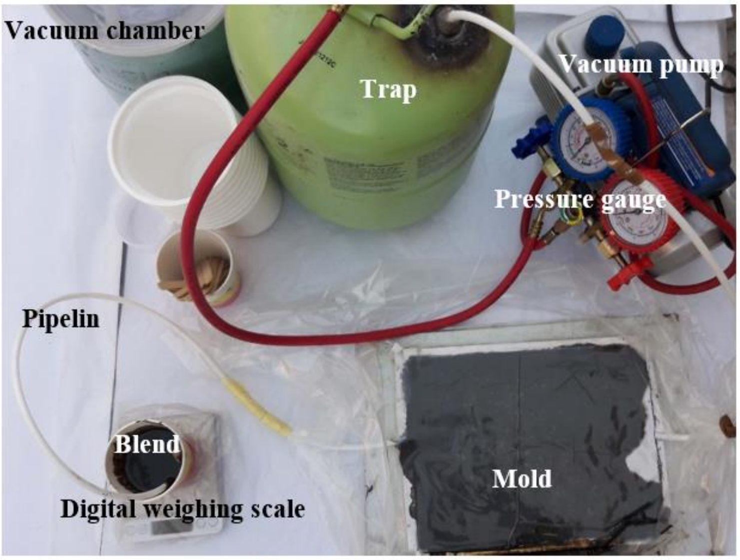

Figure 2 Vacuum infusion system (VIS).

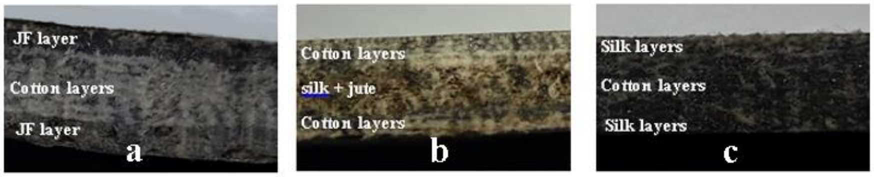

Figure 3 Hybrid type.

2.4. Characterizations

Bending and fatigue tests were used to evaluate the mechanical characteristics of the specimens.

2.4.1. Flexural Tests

The flexural (3-point bending) test was used to determine the mechanical properties of the specimens under the standard specification of the ASTM-D790, which suggests a relationship between the thickness of the specimen (t) and the distance between supports (S) of 1:16 [15]. The specimens were cut with dimensions 4x10x125 mm and S = 64 mm. The machine head is established at a standard speed of 2 [mm / min], achieved by a Tinius-Olsen h50kt machine.

2.4.2. Fatigue Tests

Rotational bending machine type HITECH with cyclical stress (HSM-20) was used to evaluate the fatigue behaviour of the specimens, which consists of an electric motor rotating at a constant number of revolutions per minute (Figure 4), the alternative cyclical bending leading to change the stresses value from minimum to maximum value repeatedly. The alternative stress is applied to the specimen at one end while the other end is held stationary.

The fatigue samples were shaped according to the specifications of the testing machine [16]. Figure 5 shows the dimensions of the fatigue samples, which are 100x10x4 mm.

Figure 4. HITECH Fatigue machine.

Figure 5 Fatigue samples.

The alternative stress value can be determined by modification of the sample end deflection and the sample effective square length, which is determined by using the following relation [16];

$$\sigma = \frac{1.5\mathrm{E}t\delta_a}{l_e^2} \qquad (1)$$

Where: σ: is the alternative stress value (MPa), E: the modulus (MPa), t : is the sample thickness (4 mm), δ_a : is the sample deflection (mm),l_e : is the sample effective length (mm).

3. Results and Discussion

3.1. Flexural Properties

Figures 6 (a, b, c and d) show the stress-strain curves of cotton composite, jute composite, silk composite and the hybrids, respectively. These curves were used to obtain the flexural properties listed in Tables 1 and 2.

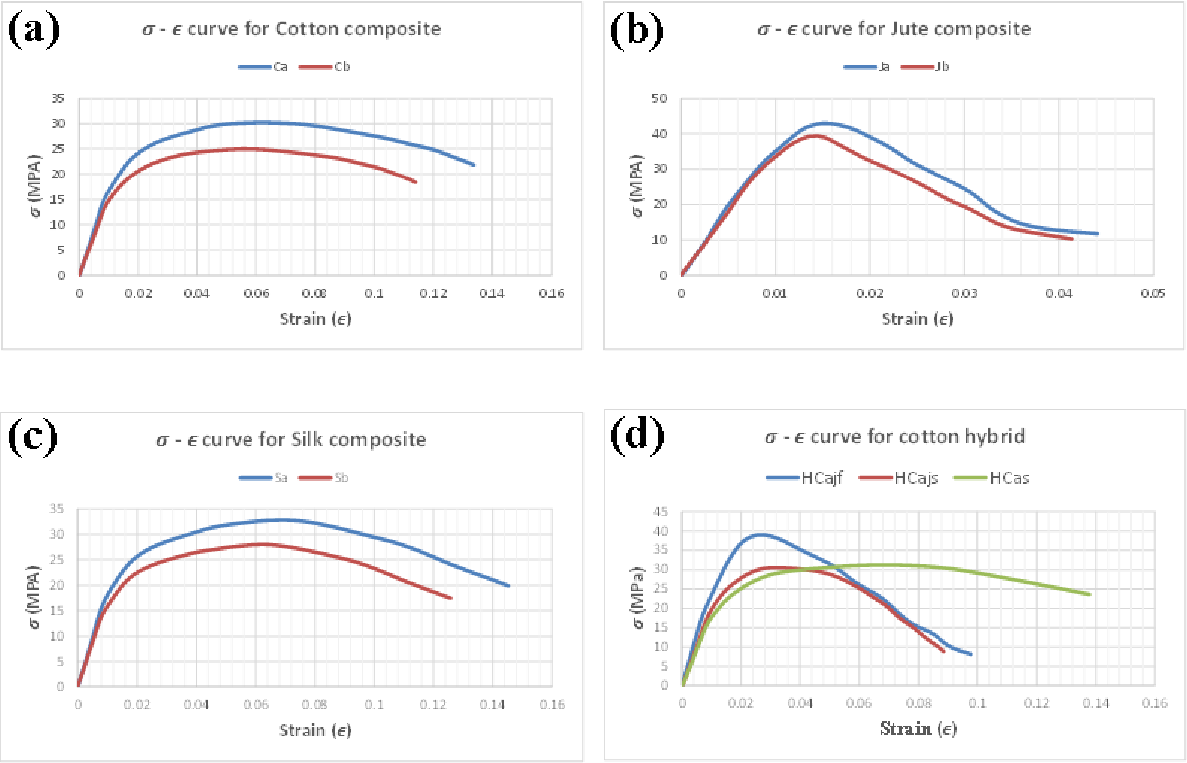

Figure 6 Shows stress-strain curves of (a) cotton composite (b) jute composite (c) silk composite (d) the hybrids

Tables 1 and 2 show the flexural tests results obtained experimentally of the composites and the hybrids, respectively, which include: flexural Modulus (E), yield stress (σ_y), maximum stress (σ_u) and maximum strain (ϵ_{max}). Comparing the flexural test results between the composites laminated by 0/90 Angle orientation and the composites laminated by a combination arrangement of 0/90 and 45/-45 Angle orientation of cotton woven, jute woven and silk woven, respectively, indicated that: the yield stress is higher by 14.7059%, 8.333% and 11.211%, While, the maximum stress is higher by 17.177 %, 8.285 % and 14.619 %.

Comparing the flexural results between the cotton composite (Ca) and the hybrids (HCajf, HCajs and HCas), the yield stress increased by 28.431 %, 8.333 % and 2.206 %, while the maximum stress increased by 29.09 %, 1.252 % and 3.331 %.

According to the above results, there are big differences in the maximum stress values of the composites due to the failures started in the blend matrix (weakest part), and reached the breaking load first, which means losing the ability to transfer load between the fibers, this evidenced a medium adhesiveness between the matrix and the reinforcements.

In addition, there are big differences in the maximum deformation values, which indicates a good interfacial bond between the fiber and the matrix for cotton and silk composite, leaving the transfer load continuing between the fibers until the breaking load.

Table 1 The flexural results of the composites.

Symbol	Flexural Modulus MPa	Yield stress MPa	Maximum stress MPa	Maximum strain
Ca	1828.571	20.4	30.2237	0.1337
Cb	1554.286	17.4	25.0321	0.1139
Ja	3849.624	42	42.9067	0.0441
Jb	3541.654	38.5	39.3519	0.0414
Sa	2006.834	21.23	32.8571	0.1452
Sb	1745.946	18.85	28.0536	0.1258

Table 2 The flexural results of the hybrids.

symbol	Flexural Modulus MPa	Yield stress MPa	Maximum stress MPa	Maximum strain
HCajf	2680.628	26.2	39.0158	0.0978
HCajs	2140.417	22.1	30.6022	0.0886
HCas	1937.547	20.85	31.2304	0.1378

3.2. Fatigue properties

Fatigue strength is an important parameter in mechanical design. For non-ferrous material called endurance limit (σ_e), S-N curves are used to determine its value. These curves were obtained by recording the applying stress on the samples and the number of cycles until failure. This process is repeated in other samples by gradually decreasing the alternating stress value [17, 18].

The endurance limit is determined on the S-N curve at one million cycles. Figures 7 (a, b, c and d) illustrate the corresponding fatigue life curves as a function of the applied altering stress (S-N curves) for cotton composite, jute composite, silk composite and the hybrids, respectively.

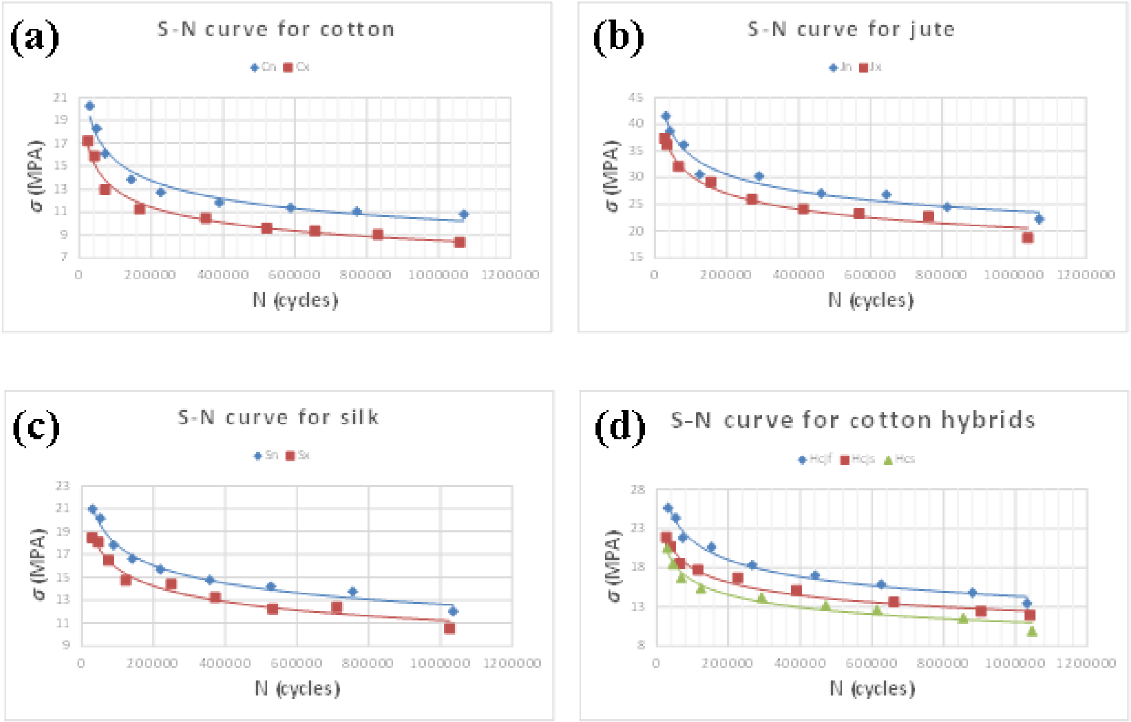

Figure 7 Shows S-N curves for (a) cotton composite (b) jute composite (c) silk composite (d) the hybrids.

The relationship between the alternating stress and the number of cycles until failure of the material is determined with an expression known as Basquin's equation, which is expressed through the simple parametric equation as follows:

$$\sigma = \mathrm{A}_c N^b \qquad (2)$$

Where: σ is the alternating stress, N is the number of cycles until failure, $\mathrm{A_c}$ is the coefficient of fatigue resistance and b is the fatigue exponent.

Tables 3 and 4 show the fatigue results of the composites and the hybrids, respectively, which include: the experimental Basquin equation, the regression (R^2), the numerical Basquin equation, the endurance limit value (σ_e) at one million cycles for experimental and numerical results and the errors percentage.

Table 3. The fatigue results of the composites

symbol	**S-N curve equations**	**R²**	**fatigue strength at 10^6 cycles (MPa)**
Ca	$\sigma = 119.57N^{-0.177}$	0.9671	10.3663
Cb	$\sigma = 107.04N^{-0.183}$	0.9803	8.5417
Ja	$\sigma = 206.97N^{-0.157}$	0.9596	23.6542
Jb	$\sigma = 208.58N^{-0.167}$	0.9680	20.7622
Sa	$\sigma = 97.498N^{-0.148}$	0.9781	12.6182
Sb	$\sigma = 85.145N^{-0.146}$	0.9614	11.3282

Table 4. The fatigue results of the hybrids

symbol	**S-N curve equations**	**R²**	**fatigue strength at 10^6 cycles (MPa)**
HCajf	$\sigma = 158.57N^{-0.174}$	0.9779	14.3292
HCajs	$\sigma = 108.26N^{-0.156}$	0.9770	12.5449
HCas	$\sigma = 115.39N^{-0.17}$	0.9555	11.0197

For fatigue results of the composites, the endurance limit of Ca is higher by 17.601 % than Cb, Ja is higher by 12.226 % than Jb, and Sa is higher by 10.223 % than Sb

By comparison of fatigue results between the cotton composites (Ca) and the hybrids, at hybridization Ca to HCajf, HCajs and HCas, the endurance limit value improved by 38.229 %, 21.017 % and 6.303 %, respectively.

The blend matrix provides the binding of the fibers, while the reinforcement fibers provide the resistance to the composite, which is affected by fibers properties, orientation, and length.

The cotton fibers have a length between 8 and 50 mm, and a diameter between 12 and 20 µm, while the Jute fibers grow from 2 to 4 meters long, and the average diameter measured is between 5 to 25 microns.

Although natural silk fiber is more expensive compared to other types of natural fibers, it has the highest ductility and longest fiber (silk fiber length reaches up to 500 meters and diameter (10-13) µm [19]. Therefore, using silk fibers in the composites and hybrids increases the ductility, which can contribute to avoiding sudden fracture.

3.4. SEM Analysis

SEM (Scanning Electron Microscopy) was used to determine the reasons (different damage mechanisms) that led to the fracture and its characteristics.

The fatigue failure mechanisms of composite materials are complex and varied, where several different damage mechanisms appear and interact, which include: matrix cracking, fiber bridging, fiber pulling-out, fiber/matrix de-bonding, fiber breakage, voids (resulting from the extraction of the fibers from the matrix) and delamination. The composite degradation is related to one or more damage mechanisms. The fracture occurs due to damage accumulation.

For Cn specimen figure 8 (a) shows that mainly fiber/matrix bonding was observed, indicating a good interface cohesion between the matrix and the reinforcement. Also, some fibers pull out of the matrix (see white arrows), voids in the fracture surface (see yellow arrows) resulting from the extraction of some fibers, cracks (see blow arrows) and regions of a rich matrix (see red circle) were observed.

Figure 8 (b) shows the micrographs obtained for the HCas hybrid. Origins of delamination between Sn and Cn layers (see red arrows) resulting from the difference in mechanical properties, cracking on the fracture surface (see yellow arrows), and voids resulting from fiber/matrix detachment (see blow arrows) were noted.

Figure 8 (c) shows SEM for the HCajf hybrid. The presence of a non -homogeneous distribution of pulling-out fibers (see yellow arrows), and cracks matrix (see red arrows) were observed. Also, a de-bonding crack in the interfacial zone between fiber and matrix (Fiber/matrix de-bonding) was noted (see white arrows).

For the HCajs hybrid, Figure 8 (d) shows that some fractured fibers were pulled out of the matrix (see white arrows), fiber/matrix de-bonded, indicating a low interfacial adhesion (see red arrows), brittle fracture for a rich matrix was noted (see green arrow), a crack was observed (see yellow arrow), voids (see blow arrows) were detected, and the part dominant mechanism of fibers/matrix broken (see the green shape) indicates a good adhesion between the fiber and the matrix, which keep them together at fracture.

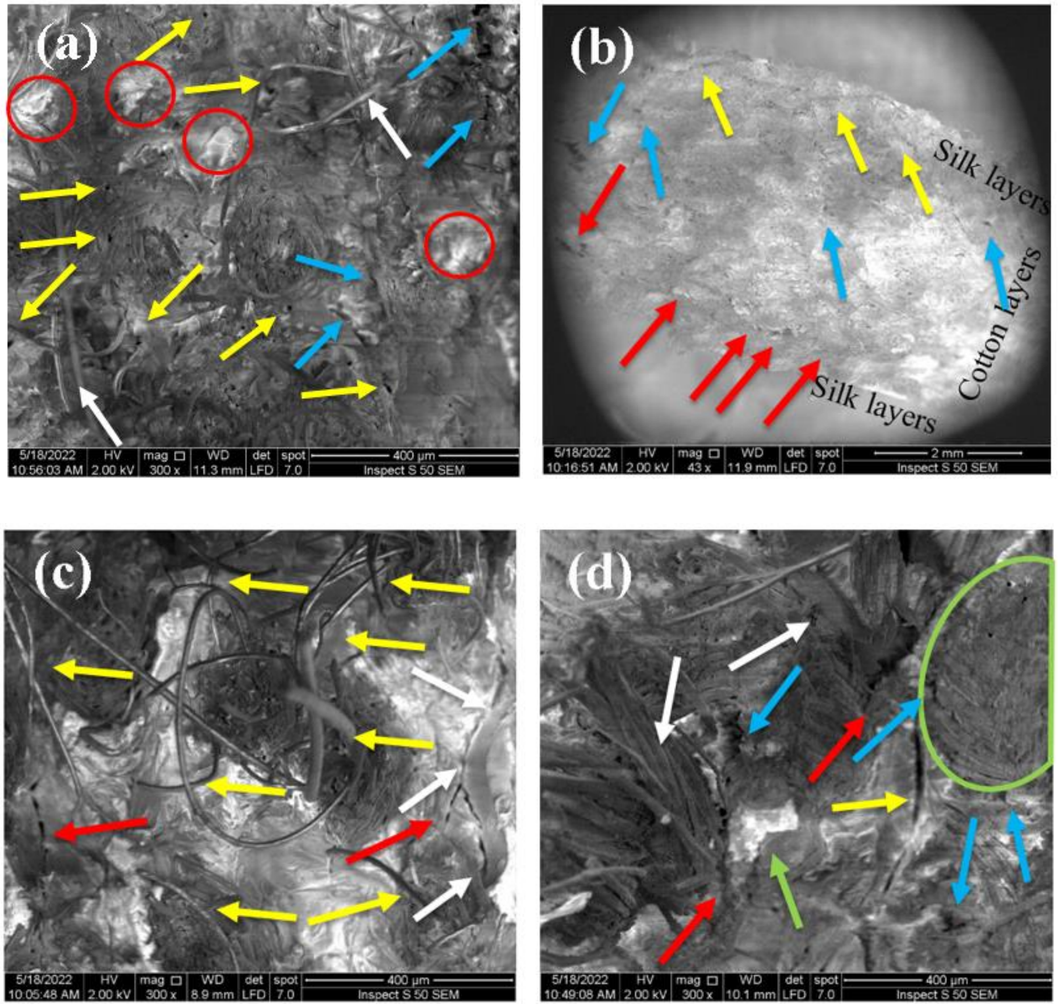

Figure 8 Shows fracture fatigue surface (SEM images) of (a) Cn, (b) HCas, (c) HCajf and (d) HCajs.

4. Conclusions

1. The mechanical properties of a composite laminated with 0/90 Angle orientation are higher than composites laminated with a combination arrangement of 0/90 and 45/-45 Angle orientation.

2. The mechanical properties of composites containing jute are higher than those containing silk and cotton, respectively.

3. Hybridization of the cotton composites by HCajf, HCajs and HCas improved the mechanical properties, respectively. The yield stress increased by 28.431 %, 8.333 % and 2.206 %, while the maximum stress increased by 29.09 %, 1.252 % and 3.331 %.

4. The fatigue life and endurance limit value of a composite laminated with 0/90 Angle orientation is higher than those laminated with a combination arrangement of 0/90 and 45/-45 Angle orientation.

5. The fatigue life and endurance limit of cotton composites were improved when hybridized by JF woven, short fibers of jute and silk distributed randomly, and silk is woven (HCajf, HCajs and HCas) sequentially.

6. Due to the composite material's heterogeneity, several types of degradation differ by their nature and the way of development. These degradations appear on different scales.

References:

[1] V. Giurgiutiu, *Structural health monitoring of aerospace composites*: Academic Press is an imprint of Elsevier, 2015.

[2] P. Pandey, *Composite materials, web-based course*, 2004.

[3] O. Faruk and M. Sain, *Biofiber reinforcements in composite materials*: Elsevier, 2014.

[4] A. K.-t. Lau and A. P. Y. Hung, *Natural fiber-reinforced biodegradable and bioresorbable polymer composites*, 2017.

[5] A. K. Kaw, *Mechanics of composite materials*: CRC press, 2005.

[6] P. Zuo, D. V. Srinivasan, and A. P. Vassilopoulos, "Review of hybrid composites fatigue," *Composite Structures*, vol. 274, p. 114358, 2021.

[7] F. C. Campbell, *Fatigue and fracture: understanding the basics*: ASM International, 2012.

[8] S. R. Daniewicz, J. C. Newman, and K. Schwalbe, *Fatigue and Fracture Mechanics* vol. 34: ASTM International, 2005.

[9] P. Ranga, S. Singhal, and I. Singh, "A review paper on natural fiber reinforced composite," *International Journal of Engineering Research & Technology*, vol. 3, pp. 467-469, 2014.

[10] K. Rajasekar, "Experimental testing of natural composite material (Jute fiber)," *IOSR Journal of Mechanical and Civil Engineering*, vol. 11, pp. 01-09, 2014.

[11] A. M. Hameed, "Preparation and studying of some properties of polymer composites reinforced with natural and artificial fibers," *Iraqi journal of physics*, vol. 14, pp. 138-147, 2016.

[12] M. K. F. M. Paudzi, M. F. Abdullah, and A. Ali, "Fatigue analysis of hybrid composites of kenaf/kevlar fibre reinforced epoxy composites," *JURNAL KEJURUTERAAN*, vol. 1, 2018.

[13] A. M. Jasim and I. A. Mahmood, "Flexural and fatigue behaviour of natural fibrous reinforced polymeric composite materials," 2022.

[14] S. Rana and R. Fangueiro, *Advanced composite materials for aerospace engineering: processing, properties and applications*: Woodhead Publishing, 2016.

[15] ASTM, "Standard test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials," in *ASTM D790-07*, ed, 2007.

[16] N. Roberts and N. R. Hart, *Alternating Bending Fatigue Machine (HSM20), Instruction Manual* vol. 150, 2001.

[17] V. Carvelli, A. Jain, and S. Lomov, *Fatigue of textile and short fiber reinforced composites*: John Wiley & Sons, 2017.

[18] B. Harris, *Fatigue in composites: science and technology of the fatigue response of fibre-reinforced plastics*: Woodhead Publishing, 2003.

[19] A. R. Bunsell, *Handbook of tensile properties of textile and technical fibres*: Elsevier, 2009.

تقييم خصائص الكلال و الانحناء لمواد مركبة ذات مزيج من البولمر مقواة بالألياف الطبيعية

الخلاصة: *تتمتع الألياف الطبيعية بمزايا في الجوانب الاقتصادية والبيئية ، مما يوفر بديلاً جذابًا في التطبيقات الصناعية المختلفة مثل قطع غيار السيارات وتشمل ؛ إدراج الباب ، لوحة القيادة ، المقاعد ، إلخ.. في هذا البحث تم تقييم خصائص الانحناء (باستخدام اختبار الانحناء بثلاث نقاط) ومنحنى S-N وقيم حدود تحمل الكلال للمواد المركبة. المادة الاساس عبارة عن المزيج يحتوي على 90٪ إيبوكسي و 10٪ بولي يوريثان بالنسب الوزنية ، ألياف طبيعية من نسيج القطن ، الجوت والحرير استخدمت للتدعيم ، والتي تم ترتيبها بزوايا 90/0 وبمزيج من 90/0 و 45 / - 45 لكل نوع من التدعيم. بعد ذلك ، تم تهجين طبقات القطن بثلاثة ترتيبات ، والتي تشمل: التداخل المتقاطع بين ألياف الكتان المنسوجة من الجوت وألياف الكتان أحادية الاتجاه (JF) كمنسوجة تفاعلية المنسوج (HCajf) ، ألياف قصيرة من الجوت والحرير موزعة عشوائيا المنسوج (HCajs)ً والحرير المنسوج (HCas). تم استخدام نظام تخلخل الفراغ (VIS) لتحضير العينات تم استخدام SEM للتحقيق في توصيف الصور المجهرية. أوضحت النتائج المقيمة أن الخواص الميكانيكية وعمر الكلال وقيمة حد التحمل للمواد المركبة المُرَتَّبة بزاوية 90/0 أعلى من المركبات المُرَتَّبة بترتيب تركيبي من زاوية باتجاه 90/0 و 45 / -45. أدى تهجين مركبات القطن (HCajf و HCajs و HCas) إلى تحسين الخواص الميكانيكية وعمر الكلال وزيادة حد التحمل بنسبة 38.229٪ و 21.017٪ و 6.303٪ على التوالي ، كما أن التهجين بألياف الحرير الطبيعي له تأثير كبير على الخواص الميكانيكية وليونة المادة المركبة. كشف اختبار SEM لعينات التعب عن عدة أنواع من آليات الضرر المرتبطة ببعضها البعض ، مما تسبب في تزايد التدهور على مستويات مختلفة.*