# Effect of fiber content and their hybridization on bending and torsional strength of hybrid epoxy composites reinforced with carbon and sugar palm fibers

**N.M.Z. Nik Baihaqi**[1)], **A. Khalina**[1), 2), *)] (ORCID ID 0000-0002-5370-6336), **N. Mohd Nurazzi**[3)] (0000-0001-7697-0511), **H.A. Aisyah**[2)] (0000-0002-4127-4740), **S.M. Sapuan**[1), 2)] (0000-0003-0627-7951), **R.A. Ilyas**[1), 2)] (0000-0001-6622-2632)

DOI: dx.doi.org/10.14314/polimery.2021.1.5

**Abstract:** This study aims to investigate the effect of fiber hybridization of sugar palm yarn fiber with carbon fiber reinforced epoxy composites. In this work, sugar palm yarn composites were reinforced with epoxy at varying fiber loads of 5, 10, 15, and 20 wt % using the hand lay-up process. The hybrid composites were fabricated from two types of fabric: sugar palm yarn of 250 tex and carbon fiber as the reinforcements, and epoxy resin as the matrix. The ratios of 85 : 15 and 80 : 20 were selected for the ratio between the matrix and reinforcement in the hybrid composite. The ratios of 50 : 50 and 60 : 40 were selected for the ratio between sugar palm yarn and carbon fiber. The mechanical properties of the composites were characterized according to the flexural test (ASTM D790) and torsion test (ASTM D5279). It was found that the increasing flexural and torsion properties of the non-hybrid composite at fiber loading of 15 wt % were 7.40% and 75.61%, respectively, compared to other fiber loading composites. For hybrid composites, the experimental results reveal that the highest flexural and torsion properties were achieved at the ratio of 85/15 reinforcement and 60/40 for the fiber ratio of hybrid sugar palm yarn/carbon fiber-reinforced composites. The results from this study suggest that the hybrid composite has a better performance regarding both flexural and torsion properties. The different ratio between matrix and reinforcement has a significant effect on the performance of sugar palm composites. It can be concluded that this type of composite can be utilized for beam, construction applications, and automotive components that demand high flexural strength and high torsional forces.

**Keywords:** sugar palm fiber, sugar palm yarn, carbon fiber, hybrid composites, epoxy resin, flexural properties, torsion properties.

## Wpływ zawartości i hybrydyzacji włókien na wytrzymałość na zginanie oraz skręcanie hybrydowych kompozytów epoksydowych wzmocnionych włóknami węglowymi i włóknami palmy cukrowej

**Streszczenie:** Zbadano wpływ dodatku przędzy z włókien palmy cukrowej o grubości 250 tex na wytrzymałość kompozytów epoksydowych wzmocnionych włóknem węglowym. Sumaryczna zawartość włókien w osnowie żywicy epoksydowej była równa 5, 10, 15 i 20% mas., a stosunek udziału przędzy palmy cukrowej do włókna węglowego wynosił 50 : 50 i 60 : 40. Właściwości mechaniczne kompozytów hybrydowych o stosunku osnowy do wzmocnienia 85 : 15 i 80 : 20 scharakteryzowano na podstawie testów na zginanie i skręcanie. Stwierdzono, że wytrzymałość na zginanie i skręcanie kompozytu epoksydowego z udziałem 15% mas. przędzy palmy cukrowej była większa niż pozostałych kompozytów niehybrydowych i wynosiła, odpowiednio, 7,40% i 75,61%. W wypadku kompozytów hybrydowych stwierdzono, że najlepszą wytrzymałość na zginanie i skręcanie wykazywały kompozyty z udziałem 15% mas. wzmocnienia w stosunku 60 : 40 włókien palmy cukrowej do włókien węglowych. Różna zawartość włókien wzmacniających w osnowie epoksydowej miała istotny wpływ na właściwości wytwarzanych kompozytów. Kompozyty tego rodzaju można wykorzystać do budowy elementów konstrukcyjnych i motoryzacyjnych, o dużej wytrzymałości na zginanie i działanie sił skręcających.

**Słowa kluczowe:** włókno palmy cukrowej, włókno węglowe, kompozyty hybrydowe, żywica epoksydowa, wytrzymałość na zginanie, wytrzymałość na skręcanie.

---

[1)] Universiti Putra Malaysia, Faculty of Engineering, 43400 Serdang, Selangor, Malaysia.

[2)] Universiti Putra Malaysia, Institute of Tropical Forestry and Forest Products (INTROP), 43400 Serdang, Selangor, Malaysia.

[3)] National Defence University of Malaysia, Center for Defence Foundation Studies, Kem Sungai Besi, 57000 Kuala Lumpur, Malaysia.

[*)] Author for correspondence: khalina.upm@gmail.com

Natural fibers have been widely used as an alternative and effective reinforcement in polymer matrices. Fillers, in the form of fibers or particles, are fabricated with polymers to obtain products with desired thermal, mechanical, and electrical properties. The properties of the composite materials are mainly dependent on their respective fiber properties. Other than that, factors affecting the properties include microstructural parameters such as fiber diameter, fiber length, fiber distribution, fiber orientation, volume fraction of the fibers, and packing arrangement of the fibers [1]. In structural applications, fiber-reinforced composites have gained a lot of market potential for their varied uses. However, this market growth is limited due to the lack of toughness of fiber-reinforced composites. The mechanical properties of natural fiber-reinforced composites are significantly improved by the incorporation of synthetic fibers [2].

Sugar palm (*Arenga pinnata*) fiber is a waste product of the agricultural industry. It is also agro-waste that can be used as a potential source of reinforcement for various biomaterial applications [3, 4]. Palm sap tapping was popular because the sap was commonly used as the base material for making traditional sugar blocks, also known as *gula kabung* or *gula enau* in the Malay language [5]. Its fruits can be processed into pickles, juices, and desserts, and they are usually canned for the food industry. Another important part, besides palm sugar and the fruits, is the black fiber called ijuk. The black fiber has many applications and uses including the manufacturing of brooms, paint brushes, septic tank base filters, clear water filters, door mats, carpets, and ropes for sea cordage [6]. Sugar palm fiber offers high tensile strength (similar to the strength of coir, kenaf, bamboo, and hemp fibers within the range 138.7 to 270 MPa) that is durable before degradation. It is a fairly durable fibrous material that has a good resistance to sea water and is less affected by heat and moisture damage compared to coir fiber [7, 8]. Many studies have been conducted on the properties of sugar palm fiber-reinforced composites. Sugar palm fibers have an excellent composite potential, unlike other natural fibers such as kenaf, jute, oil palm, sugarcane bagasse, pineapple leaf, and banana pseudo stem fibers [9–15].

Synthetic fibers such as glass fiber, carbon fiber, and Kevlar are man-made fibers that have been used dominantly in the composite industry, especially in aerospace, automotive, and sports equipment. Many studies reveal the promising performance of synthetic fibers as a good mechanical and thermal material enhancer [16–19]. Nonetheless, the negative environmental and health effects associated with synthetic fibers have led to the increasing use of natural fibers such as jute, ramie, bamboo, kenaf, oil palm, and wood as promising alternative reinforcements. However, the desired tensile strengths and modulus of glass fibers are visibly much higher than natural fibers [20]. Researchers and engineers are enticed by the numerous merits of natural fibers over synthetic fibers. The escalating use of natural fibers can be ascribed to their availability, processability, renewability, recyclability, and biodegradability [21]. Besides, natural fibers have several advantages such as comparable tensile strength properties, low density, and less energy consumption during processing over synthetic fibers [22]. Despite the advantages of natural fibers, they have major drawbacks such as the ability to absorb water (hydrophilic in nature), strength degradation, lack of thermal stability, and low impact properties [23–25]. These drawbacks can be improved by the following: (i) hybridization either with natural or synthetic fiber [26, 27] and (ii) modification through chemical treatments [28, 29]. Table 1 shows the main comparison between natural fibers and synthetic fibers [30].

**Table 1. The comparison of properties between natural fibers and synthetic fibers [30]**

| Properties | Natural fibers | Synthetic fibers |
|---|---|---|
| Density | Light | Twice than natural fibers |
| Cost | Low-cost | Higher than natural fibers |
| Renewability | Yes | No |
| Energy consumption | Low | High |
| Distribution | Wide | High |
| $CO_2$ neutral | Yes | No |
| Health risk when inhaled | No | Yes |
| Disposal | Biodegradable | Yes, not biodegradable |

The development of hybrid composite materials is based on the reinforcement of two or more fibers in a single matrix. Research reveals that the behavior of hybrid composites appears to be the weighted sum of individual components that have a more favorable balance between the advantages and disadvantages in any composite material [31]. Furthermore, the hybridization of different fibers is advantageous because one particular fiber can complement the limitations of another fiber. As a result, it has increased fatigue life, better fracture toughness, lower notch sensitivity, and cost reduction for engineering applications [33–35] compared to single fiber-reinforced composites [32]. The benefits of hybridization compared to composite systems, even if they are only partial, are mainly in terms of ecological and economical effects. Natural fibers are biodegradable and lighter than glass fiber. This feature allows the reduction of fuel use by the automotive and aerospace industry [36].

There are several factors affecting the mechanical properties of hybrid composites, such as hybridization design, fiber volume or weight fraction, nature of the matrix, fiber length, fiber composition, and fiber–matrix interface [34, 37]. One work [38] stated that much research reveals that the behavior of hybrid biocomposites is the function of the weighted sum of individual components with a favorable balance between the benefits and drawbacks of composite materials. Several studies also investigated the effect of hybridization between a natural fiber and a synthetic fiber (carbon fiber and glass fiber) in a single matrix [39–45].

The objective of this study is to compare the mechanical properties, *i.e.*, flexural and torsion properties, of non-hybrid sugar palm yarn fiber-reinforced epoxy composites and the effect of the hybridization of sugar palm yarn fiber with carbon fiber-reinforced epoxy composites at different fiber ratios for automotive purposes.

## EXPERIMENTAL PART

### Materials

The sugar palm fiber was purchased from Hafiz Adha Enterprise, Kampung Kuala Jempol, Negeri Sembilan, Malaysia. Then, the yarn sugar palm fiber (250 tex) was obtained using published protocols [46]. The carbon fiber was supplied by Sky Tech Malaysia Sdn. Bhd., and the epoxy resin (RTM grade, 40% styrene content, density of 1.025 g/cm$^3$) was purchased from CCP Composites Resins Malaysia Sdn. Bhd. Table 2 shows the physical and mechanical properties of the materials used.

### Preparation process of the composites

The sugar palm yarn with a linear density of 250 tex was produced by the spinning process, which was in accordance with the procedures specified in previous studies [46, 48]. The composite was prepared according to the mix ratio from the instruction labels. The mix ratio of 3A : 1B was used, where A is for epoxy and B is for hardener. The mixed resin was poured over the fibers and cured at room temperature for 24 h.

For the fabrication of hybrid composites, the ratios between matrix and reinforcement of 85 : 15 and 80 : 20 were selected. The ratios of reinforcement between the sugar palm yarn fiber and carbon yarn fiber of 60 : 40 and 50 : 50 were selected. The carbon fiber was manually wrapped in the PVC pipe and the bundle of sugar palm yarn fiber as per weight percentage (wt %) (Fig. 1). Figure 2 shows the overall preparation process of the composites.

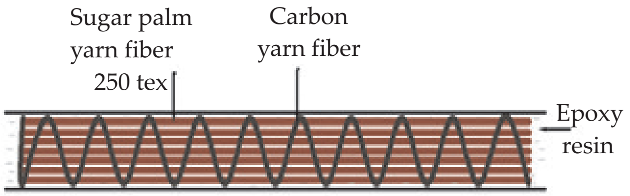

**Fig. 1. Schematic diagram for the position of carbon yarn fiber wrapped around the sugar palm yarn fiber**

### Methods of testing

The flexural test was performed using the three-point bending method using an Instron 3365 test machine according to ASTM D790. The length and diameter of the cylindrical samples were 120 and 16 mm, respectively. The crosshead speed was set at 5 mm/min and the support span-to-depth ratio was 16 : 1. The coefficient of variance (*COV*) was calculated using Eq. (1).

$$COV = \frac{\text{standard deviation}}{\text{mean of flexural strength}} \cdot 100\% \qquad (1)$$

The torsional test was conducted according to ASTM D5279 using the torsion test machine with the capacity of 50 Nm. The length and diameter of the samples were 120 and 16 mm, respectively. A hexagonal socket was used to fix the sample to the torsion test machine. The sample was rotated by the spindle, and the values of torque and angle were recorded at the same time. Then, the shear modulus of the sample was calculated using Eq. (2).

$$G = \frac{Tl}{J^T \varphi} \qquad (2)$$

where: $G$ – the shear modulus or modulus of elasticity, $T$ – the applied torque, $l$ – the length of object in which torque is applied, $J^T$ – the polar moment of inertia, $\varphi$ – the angle of twist.

**Table 2. Physical and mechanical properties of sugar palm fiber [48], carbon fiber [47], and epoxy (EpoxAmite 100 with 102 hardener) composite**

| Properties | Material | | |
|---|---|---|---|
| | Sugar palm fiber | Carbon fiber | Epoxy matrix |
| Density, g/cm$^3$ | 1.292 | 1.1 to 1.9 | 1.13 |
| Tensile strength, MPa | 156.96 | 4000 | 56.40 |
| Tensile modulus, GPa | 4.96 | 230 to 240 | 3.10 |
| Elongation at break, % | 7.98 | 1.4 to 1.8 | 2.45 |
| Flexural strength, MPa | – | – | 84.25 |
| Flexural modulus, GPa | – | – | 2.92 |

**Fig. 2. Photograph of: a) raw sugar palm fiber, b) combed sugar palm fiber, c) spinning process [44, 49], d) sugar palm yarn fiber, e) weighed epoxy resin, f) inserted sugar palm yarn fiber into the PVC pipe, g) the pouring process, h) cured composite**

## RESULTS AND DISCUSSION

### Flexural properties

Figure 3 shows the flexural results for the non-hybrid composites. The figure shows an increasing trend up to 15 wt % of sugar palm yarn fiber loading before it declines at 20 wt % of fiber loading. The highest flexural strength recorded was 87 MPa and the flexural modulus recorded was 3.3 GPa at 15 wt %. The higher value of flexural strength obtained at 15 wt % fiber loading composite was because the composites can withstand more load with an increase of corresponding fiber volume in the composite. Higher numbers of fibers correspond to an effective stress transfer within the matrix. Thus, a composite with higher fiber loading could transfer more stress. In addition, the increment was due to the better interfacial adhesion (wettability) between the sugar palm yarn fiber with the epoxy matrix. One publication [50] highlights factors that affect flexural strength such as interfacial strength, degree of cure, and fiber volume fraction that are more complex than a direct correlation. During the flexural test, the vertical load is transferred from the center top surface of the specimen to the bottom surface. The top surface was under compression deformation while the bottom surface was under tensile deformation.

The flexural strength and flexural modulus decreased at 20 wt % of fiber loadings with 85 MPa and 3.1 GPa, which are equivalent to 2.3% and 6%, respectively. The increased fiber–fiber interactions and the inefficiency of the matrix to penetrate and cover the fibers could result in a low stress transfer mechanism [46]. Lower wetting properties were observed due to the large amount of sugar palm fibers that resulted in less resin penetration. Besides, the low contact area between the matrix with the sugar palm yarn fiber is due to the higher packing effect between the fiber that reduces the flexural properties.

Generally, lower coefficient of variance (*COV*) reflects less variation in the results; thus, it has higher consistency and reliability [11]. Based on the *COV* result shown in Table 3, the fiber loading at 15 wt % yielded the lowest *COV* of 8.84%. This result suggests that the fiber loading produced the most consistent and uniform stress transferred from the matrix to the fibers during the applied stress. The highest *COV* of 21.72% was obtained from 20 wt % of fiber loading. It is most difficult to control the fabrication process of the highest fiber loading due to the low wettability between the fiber and the matrix. Hence, it leads to a difficult and inefficient stress transfer.

**T a b l e 3. Flexural strength *COV* of the composites**

| Sample | | *COV*, % |
|---|---|---|
| Non-hybrid composites | 5 wt % | 14.30 |
| | 10 wt % | 12.19 |
| | 15 wt % | 8.84 |
| | 20 wt % | 21.72 |
| Hybrid composites | 15 wt % – 50 : 50 | 16.73 |
| | 15 wt % – 60 : 40 | 14.24 |
| | 20 wt % – 50 : 50 | 18.21 |
| | 20 wt % – 60 : 40 | 18.49 |

The difference between the highest and the lowest *COV* was 12.88%, indicating a significant gap in the precision for flexural strength mean between 15 and 20 wt %. This result can be justified by looking at the fiber weight percentage between the two samples. Based on the results, it can be deducted that the 15 wt % sample has a better fiber matrix interaction, which resulted in a more precise and consistent strength throughout the sample.

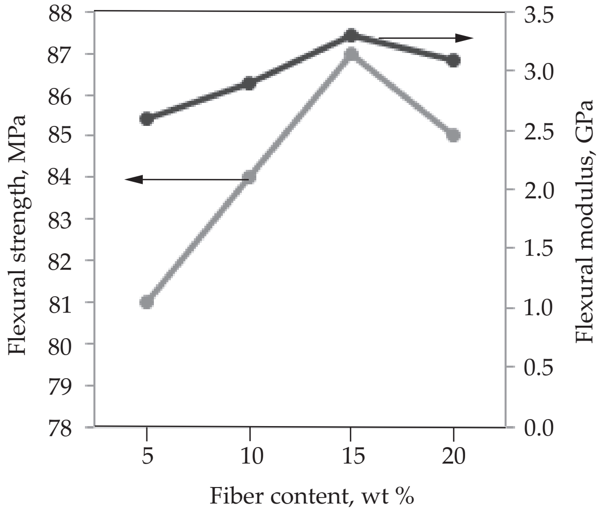

**Fig. 3. Flexural properties for non-hybrid epoxy composites reinforced with sugar palm fiber**

Figure 4 shows the flexural properties of the hybrid composites. The best flexural properties were achieved from 15 wt % of reinforcement at the fiber ratio of 60 : 40. The corresponding flexural strength and flexural modulus for the composite sample were 118 MPa and 3.8 GPa, respectively. The result shows that the ratio of sugar palm yarn fiber can increase up to 60 : 40 for the flexural strength and flexural modulus. This result is due to the effective layering design and the position of sugar palm yarn fiber at the core or tendon for the composite structure (Fig. 1). The increasing weight percentage of sugar palm yarn fiber loading that is located at the center acted as an efficient rigid filler in absorbing the flexural stress. In the case of hybrid composites, the additional presence of carbon fiber increases the flexural strength by about 35% and flexural modulus by about 15%. It is influenced by the synergistic effect of carbon fiber that has excellent specific tensile strength and modulus. The lowest *COV* was recorded from 15 wt % reinforcement at 60 : 40 fiber ratio, which is 14.24%. This value indicates that the reinforcement loading and ratio can yield the highest uniformity for flexural strength and flexural modulus mean.

## Torsion properties

Figure 5 shows the results of the torsional forces versus the angle of twist at varying fiber loadings for non-hybrid composites that are obtained from the torsion test machine. The maximum torsional strength on the non-hybrid composites was 41.9 Nm at an angle of twist at 50° for the composite with 15 wt % of fiber loading. This result shows that the fiber loading of 15 wt % is the optimum fiber loading to provide an effective stress transfer and sustain the ultimate shearing force upon the increasing of angle of twist. This also could be due to the

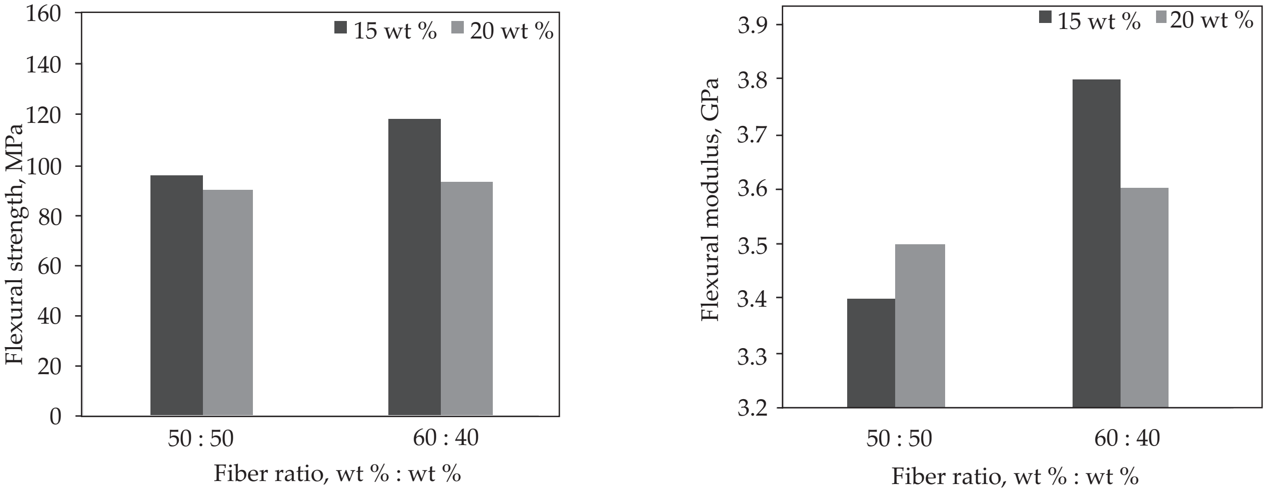

**Fig. 4. Flexural properties for hybrid composites**

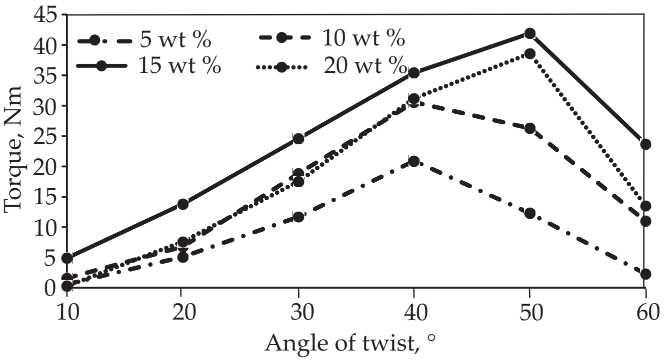

**Fig. 5. Torsion properties of the non-hybrid epoxy composites reinforced with sugar palm fiber**

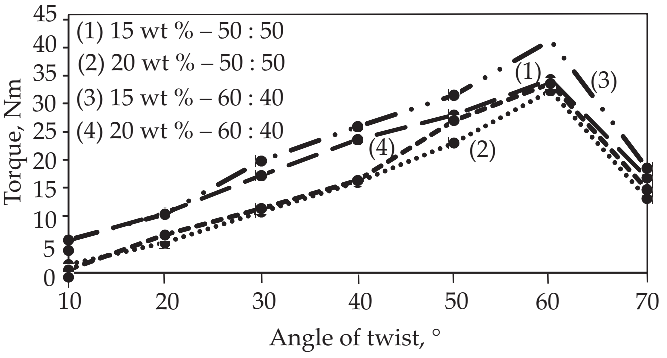

**Fig. 6. Torsion properties of the hybrid composite**

excellent wettability and contact area between the sugar palm yarn fiber with the epoxy matrix, hence improving the stress mechanism. When the fiber loading is above 20 wt %, the torsional strength decreased to 7.88% at 50° angle of twist. This result might be due to the high packing arrangement of sugar palm yarn fiber that leads to excessive fiber–fiber interactions. Hence, it reduces the effectiveness where stress is to be transferred from the matrix to the packed sugar palm yarn fibers.

The optimum angle of twist was at 50° for 15 and 20 wt % of fiber loading composites, where the torsional strength dropped at 60° angle of twist. The twisting of up to 60° of composites caused fiber compactness and increased the fiber–fiber surface contact. As a result, the effectiveness of the stress transfer mechanism from the matrix to the fibers resisted, and it was difficult to maintain the stability of the composite structure stiffness, which leads to a reduced torsional strength. The optimum angle of twist was at 50° for 10 and 20 wt %. The stress was transferred to the rich resin area, which was brittle and not efficiently supported by the sugar palm yarn fiber as a result of the reinforcement upon the increased angle of twist. Figure 6 presents the torsional properties of hybrid composites at varied angles of twist. The maximum torsional strength for hybrid composites was 41.3 Nm at 15 wt % of reinforcement with the fiber ratio of 60 : 40. The extended failure for all composites was up to 60° angle of twist with the addition of carbon fiber (Fig. 7). This situation happened due to the superior strength and modulus of carbon fibers that can maintain the stability of the circular position until deformation occurs.

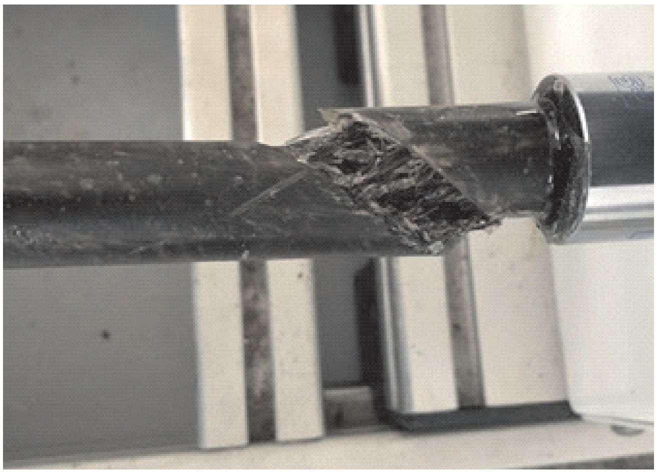

**Fig. 7. The failure test result of the non-hybrid epoxy composites reinforced with 20 wt % of sugar palm fiber**

The shear modulus is defined as rigidity, and it is a measure for the ability of a material to resist transverse deformations and elastic behavior for deformations after the material returns to its original structure. Large shearing forces can lead to flow and permanent deformation and failure. Table 4 presents the results for the shear modulus of the hybrid composites. The shear modulus for non-hybrid and hybrid samples was reduced when the angle of twist was increased.

**Table 4. Shear modulus of composites at 50° and 60° angle of twist**

| Sample | | Shear modulus at 50°, GPa | Shear modulus at 60°, GPa |
|---|---|---|---|
| Non-hybrid composites | 5 wt % | 0.263 | 0.041 |
| | 10 wt % | 0.563 | 0.196 |
| | 15 wt % | 0.897 | 0.423 |
| | 20 wt % | 0.826 | 0.241 |
| Hybrid composites | 15 wt % – 50 : 50 | 0.599 | 0.612 |
| | 15 wt % – 60 : 40 | 0.674 | 0.737 |
| | 20 wt % – 50 : 50 | 0.492 | 0.576 |
| | 20 wt % – 60 : 40 | 0.578 | 0.599 |

## CONCLUSIONS

– The higher flexural strength and flexural modulus of non-hybrid composites were achieved at 15 wt % of sugar palm yarn fiber loading with 87 MPa and 3.3 GPa, respectively. For the hybrid composite, 15 wt % of reinforcement with the ratio of 60 : 40 revealed the highest flexural strength and flexural modulus, which were 118 MPa and 3.8 GPa, respectively.

– The higher torque at 50° angle of twist and shear modulus were achieved at 15 wt % of sugar palm yarn fiber loading with 41.9 Nm and 0.897 GPa, respectively.

For the hybrid composite, 15 wt % of reinforcement at the ratio of 60 : 40 reveals the highest torque value of 41.4 Nm at 60° angle of twist and shear modulus of 0.737 GPa.

*ACKNOWLEDGMENTS*

*The authors wish to thank Universiti Putra Malaysia (UPM) for providing research grants (GP-IPB) with the project number GP-IPB/2014/9441502 and excellent facilities.*

## REFERENCES

[1] Paul S.A., Boudenne A., Ibos L. *et al.*: *Composites Part A: Applied Science and Manufacturing* **2008**, *39* (*9*), 1582. https://doi.org/10.1016/j.compositesa.2008.06.004

[2] Zin M.H., Abdan K., Norizan M.N.: "Structural Health Monitoring of Biocomposites, Fibre-Reinforced Composites and Hybrid Composites" Woodhead Publishing, 2019. https://doi.org/10.1016/B978-0-08-102291-7.00001-0

[3] Ilyas R.A., Sapuan S.M., Atiqah A. *et al.*: *Polymer Composites* **2020**, *41* (*2*), 459. https://doi.org/10.1002/pc.25379

[4] Ilyas R.A., Sapuan S.M., Ibrahim R. *et al.*: *Journal of Materials Research and Technology* **2019**, *8* (*3*), 2753. https://doi.org/10.1016/j.jmrt.2019.04.011

[5] Ishak M.R., Leman Z., Sapuan S.M. *et al.*: "Key Engineering Materials", Trans Tech Publications Ltd., 2011, pp. 1153–1158. https://doi.org/10.4028/www.scientific.net/KEM.471-472.1153

[6] Ishak M.R., Sapuan S.M., Leman Z. *et al.*: *Carbohydrate Polymers* **2013**, *91* (*2*), 699. https://doi.org/10.1016/j.carbpol.2012.07.073

[7] Maisara A.M.N., Ilyas R.A., Sapuan S.M. *et al.*: *International Journal of Recent Technology and Engineering* **2019**, *8*, 510. https://doi.org/10.35940/ijrte.B1100.0782S419

[8] Nurazzi N.M., Khalina A., Sapuan S.M. *et al.*: *Journal of Mechanical Engineering and Sciences* **2017**, *11* (*2*), 2650. https://doi.org/10.15282/jmes.11.2.2017.8.0242

[9] Ilyas R.A., Sapuan S.M., Ishak M.R., Zainudin E.S.: *Carbohydrate Polymers* **2018**, *202*, 186. https://doi.org/10.1016/j.carbpol.2018.09.002

[10] Jumaidin R., Sapuan S.M., Jawaid M. *et al.*: *International Journal of Biological Macromolecules* **2017**, *97*, 606. https://doi.org/10.1016/j.ijbiomac.2017.01.079

[11] Sanyang M.L., Sapuan S.M., Jawaid M. *et al.*: *Polymers* **2015**, *7* (*6*), 1106. https://dx.doi.org/10.3390/polym7061106

[12] Rashid B., Leman Z., Jawaid M. *et al.*: *International Journal of Precision Engineering and Manufacturing* **2016**, *17* (*8*), 1001. https://doi.org/10.1007/s12541-016-0122-9

[13] Atiqah A., Jawaid M., Sapuan S.M. *et al.*: *Composite Structures* **2018**, *202*, 954. https://doi.org/10.1016/j.compstruct.2018.05.009

[14] Ilyas R.A., Sapuan S.M., Ishak M.R. *et al.*: "Sugar Palm Biofibers, Biopolymers, and Biocomposites", Taylor & Francis Group, 2018, pp. 189–220.

[15] Mohammed B.R., Leman Z., Jawaid M. *et al.*: *BioResources* **2017**, *12* (*2*), 3448. https://doi.org/10.15376/biores.12.2.3448-3462

[16] Singh T., Gangil B., Patnaik A. *et al.*: *Materials Research Express* **2018**, *6* (*2*), 025704. https://doi.org/10.1088/2053-1591/aaee30

[17] Nurazzi N.M., Khalina A., Sapuan S.M., Rahmah M.: *Materials Research Express* **2018**, *5* (*4*), 045308. https://doi.org/10.1088/2053-1591/aabc27

[18] Zin M.H., Abdan K., Mazlan N. *et al.*: *Composites Part B: Engineering* **2019**, *177*, 107306. https://doi.org/10.1016/j.compositesb.2019.107306

[19] Aisyah H.A., Paridah M.T., Sapuan S.M. *et al.*: *International Journal of Polymer Science* **2019**, *2019*, ID 5258621. https://doi.org/10.1155/2019/5258621

[20] Mochane M.J., Mokhena T.C., Mokhothu T.H. *et al.*: *Express Polymer Letters* **2019**, *13* (*2*), 159. https://doi.org/10.3144/expresspolymlett.2019.15

[21] Sanyang M.L., Sapuan S.M., Jawaid M. *et al.*: *Renewable and Sustainable Energy Reviews* **2016**, *54*, 533 https://doi.org/10.1016/j.rser.2015.10.037

[22] Satyanarayana K.G., Arizaga G.G., Wypych F.: *Progress in Polymer Science* **2009**, *34* (*9*), 982. https://doi.org/10.1016/j.progpolymsci.2008.12.002

[23] Adekunle K., Cho S.W., Patzelt C. *et al.*: *Journal of Reinforced Plastics and Composites* **2011**, *30* (*8*), 685. https://doi.org/10.1177/0731684411405874

[24] Alawar A., Hamed A.M., Al-Kaabi K.: *Composites Part B: Engineering* **2009**, *40* (*7*), 601. https://doi.org/10.1016/j.compositesb.2009.04.018

[25] Mohd Nurazzi N., Khalina A., Sapuan S.M. *et al.*: *Pertanika Journal of Science & Technology* **2017**, *25* (*4*), 1085.

[26] Nurazzi N.M., Khalina A., Sapuan S.M. *et al.*: *Journal of Materials Research and Technology* **2020**, *9* (*2*), 1606. https://doi.org/10.1016/j.jmrt.2019.11.086

[27] Mostafa N.H.: *Materials Research Express* **2019**, *6* (*8*), 085102. https://doi.org/10.1088/2053-1591/ab21f9

[28] Zin M.H., Abdan K., Norizan M.N., Mazlan N.: *Pertanika Journal of Science & Technology* **2018**, *26* (*1*), 161.

[29] Aruchamy K., Subramani S.P., Palaniappan S.K. *et al.*: *Journal of Materials Research and Technology* **2020**, *9* (*1*), 718. https://doi.org/10.1016/j.jmrt.2019.11.013

[30] Sreekumar P.A., Thomas S.: "Properties and Performance of Natural-Fibre Composites", Woodhead Publishing, 2008, pp. 67–126. https://doi.org/10.1533/9781845694593.1.67

[31] John M.J., Thomas S.: *Carbohydrate Polymers* **2008**, *71* (*3*), 343.

https://dx.doi.org/10.1016/j.carbpol.2007.05.040

[32] Shahzad A.: *Journal of Reinforced Plastics and Composites* **2011**, *30* (*16*), 1389. https://doi.org/10.1177/0731684411425975

[33] Venkata Reddy G., Venkata Naidu S., Shobha Rani T.: *Journal of Reinforced Plastics and Composites* **2008**, *27* (*16–17*), 1789. https://doi.org/10.1177/0731684407087380

[34] Thwe M.M., Liao K.: *Composites Part A: Applied Science and Manufacturing* **2002**, *33* (*1*), 43. https://doi.org/10.1016/S1359-835X(01)00071-9

[35] Nguyen A.V., Charlet K., Bouzgarrou B.C. *et al.*: "Key Engineering Materials", Trans Tech Publications Ltd., 2019, pp. 101–106. https://doi.org/10.4028/www.scientific.net/KEM.801.101

[36] Vieira C.A.B., Susin S.B., Estevão F. *et al.*: *Materials Research* **2009**, *12* (*4*), 433. http://dx.doi.org/10.1590/S1516-14392009000400011

[37] Pothan L.A., Thomas S., George J.: 12th International Conference on Composite Materials, Paris, France 1999, p. 1267.

[38] Mishra S., Mohanty A.K., Drzal L.T. *et al.*: *Composites Science and Technology* **2003**, *63* (*10*), 1377. https://doi.org/10.1016/S0266-3538(03)00084-8

[39] Khanam P.N., Khalil H.A., Jawaid M. *et al.*: *Journal of Polymers and the Environment* **2010**, *18* (*4*), 727. https://doi.org/10.1007/s10924-010-0210-3

[40] Fiore V., Valenza A., Di Bella G.: *Journal of Composite Materials* **2012**, *46* (*17*), 2089. https://doi.org/10.1177/0021998311429884

[41] Nor A.F.M., Sultan M.T.H., Jawaid M. *et al.*: *BioResources* **2018**, *13* (*2*), 4404. https://doi.orh/10.15378/biores.13.2.4404-4415

[42] Aslan M., Tufan M., Küçükömeroğlu T.: *Composites Part B: Engineering* **2018**, *140*, 241. https://doi.org/10.1016/j.compositesb.2017.12.039

[43] Bharath K.N., Sanjay M.R., Jawaid M. *et al.*: *Journal of Industrial Textiles* **2019**, *49* (*1*), 3. https://doi.org/10.1177/1528083718769926

[44] Mohd Nurazzi N., Khalina A., Sapuan S.M., Ilyas R.A.: *Polimery* **2019**, *64*, 665. https://dx.doi.org/10.14314/polimery.2019.10.3

[45] Manuneethi Arasu P., Karthikayan A., Venkatachalam R.: *Polimery* **2019**, *64*, *499*. https://dx.doi.org/10.14314/polimery.2019.7.6

[46] Norizan M.N., Abdan K., Salit M.S., Mohamed R.: *Journal of Physical Science* **2017**, *28* (*3*), 115. https://doi.org/10.21315.jps2017.283.8

[47] Mahjoub R., Yatim J.M., Sam A.R.M., Hashemi S.H.: *Construction and Building Materials* **2014**, *55*, 103. https://doi.org/10.1016/j.conbuildmat.2014.01.036

[48] Nurazzi N.M., Khalina A., Chandrasekar M. *et al.*: *Polimery* **2020**, *65*, 115. https://dx.doi.org/10.14314/polimery.2020.2.5

[49] Norizan M.N., Abdan K., Salit M.S., Mohamed R.: *Sains Malaysiana* **2018**, *47* (*4*), 699. https://dx.doi.org/10.17576/jsm-2018-4704-07

[52] Wulfsberg J., Herrmann A., Ziegmann G. *et al.*: *Procedia Engineering* **2014**, *81*, 1601. https://doi.org/10.1016/j.proeng.2014.10.197

*Received 9 VI 2020.*