Mechanical properties of sugar palm yarn/woven glass fiber reinforced unsaturated polyester composites: effect of fiber loadings and alkaline treatment

N. Mohd Nurazzi[1), A. Khalina[1), 2), *), S.M. Sapuan[1), 2), R.A. Ilyas[2)

DOI: dx.doi.org/10.14314/polimery.2019.10.3

Abstract: In this paper, hybrid sugar palm yarn and glass fiber reinforced unsaturated polyester composites were investigated in relation to the effects of fiber loadings and alkaline treatment on the composite mechanical properties, such as tensile, flexural, impact and compression strength. The composites were fabricated at a weight ratio of matrix to reinforcement of 70 : 30 and 60 : 40, respectively, while the ratio of sugar palm yarn fiber to glass fiber was selected at 70 : 30, 60 : 40 and 50 : 50, respectively. The results revealed that the mechanical properties of the hybrid composites were increased with an increase of glass fiber loading for both 30 wt % and 40 wt % reinforcement content. The alkaline treatment of the sugar palm fibers have advantageous effect on the hybrid composite performance. The overall results indicated that the developed hybrid composites can be used as an alternative material for glass fiber reinforced polymer composites for various structural applications.

Keywords: glass fiber, hybrid composites, mechanical properties, sugar palm fiber, yarn fiber, unsaturated polyester resin.

Wpływ zawartości włókien i obróbki alkalicznej na właściwości mechaniczne kompozytów z nienasyconej żywicy poliestrowej wzmacnianych włóknem szklanym i włóknem palmy cukrowej

Streszczenie: Zbadano wpływ zawartości włókien i ich obróbki alkalicznej na właściwości mechaniczne wzmacnianych włóknem szklanym kompozytów nienasyconej żywicy poliestrowej z włóknami palmy cukrowej. Oceniano wytrzymałość kompozytów na rozciąganie, zginanie, uderzenie i ściskanie. Wytworzone kompozyty zawierały 30 oraz 40% mas. włókien, przy stosunku masowym włókien palmy cukrowej do włókien szklanych 70/30, 60/40 i 50/50. Stwierdzono, że wytrzymałość mechaniczna kompozytów hybrydowych zwiększa się ze wzrostem zawartości włókna szklanego, a obróbka alkaliczna włókien palmy cukrowej wywiera korzystny wpływ na właściwości zawierających ją kompozytów hybrydowych. Uzyskane wyniki wskazują, że opracowane kompozyty hybrydowe mogą być stosowane jako materiał alternatywny dla kompozytów polimerowych wzmacnianych jedynie włóknem szklanym.

Słowa kluczowe: włókno szklane, kompozyty hybrydowe, właściwości mechaniczne, włókno palmy cukrowej, włókno przędzy, nienasycona żywica poliestrowa.

The increased demands for engineering materials have driven a broad range of research and development of new and improved materials especially from the composites industry. Since most natural fibers used today are at the leading edge of material technology, an intensive development of their uses in advanced applications is becoming harder to ignore. The main advantages of natural fibers over synthetic fibers are their relatively low mass and specific density, high specific strength, renewability, biodegradability, and abundance [1, 2]. The use of natural fiber composites is actually referred to the utilization of natural sources in polymer industry, reducing the dependence on petroleum resources and the carbon dioxide (CO_2) emissions due to decreasing need for plastic burning [3]. However, these promising fibers also have several drawbacks, such as their hydrophilic nature, which leads to the problem of incompatibility with some polymeric matrices. They contain hydroxyl (-OH) groups from cel-

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

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

[*)] Author for correspondence;
e-mail: khalina.upm@gmail.com

lulose, hemicellulose and lignin, which may be involved in the hydrogen bonding within the cellulose molecules, thereby reducing the interfacial adhesion with the polymeric matrix.

The main problem often encountered in its use is the fiber-matrix adhesion due to the incompatibility between the hydrophilic natural fibers (polar) and the hydrophobic polymer matrix (non-polar) [4]. Wambua *et al.* [5] listed the physical and chemical treatments, that can help to overcome the disadvantages of natural fibers. The properties of natural fiber reinforced composites can be influenced by fiber loading. In general, a high fiber loading is required to achieve high performance of the composites. Therefore, the effect of fiber loading on the properties of natural fiber reinforced composites is particularly significant. It is often observed that the increase in fiber content results in an improvement in the mechanical properties [6, 7].

The development of hybrid composite materials with the reinforcement based on two or more types of fibers in a single matrix remains in infancy. Research has revealed that the behavior of hybrid composites appears to be simply a weighted sum of the individual components in which there is a more promising balance between the advantages and disadvantages inherent in any composite material [8]. In other words, the advantage of producing hybrid composites reinforced with different types of fibers is that one kind of reinforcement could complement the limitations of another. As a result, a balance of mechanical performance and cost reduction for engineering applications could be achieved [9, 10]. The effect of hybridization between a natural fiber and synthetic fiber in a single matrix has been studied [11–17]. It has been found, that optimization of fiber loadings have shown favorable effect on the improvement of physical and mechanical properties. According to Atiqah *et al.* [18], the limitation of fiber loading in hybrid composites is generally showed at a maximum of 50%.

Therefore, in this work an attempt has been taken to develop a hybrid composite combining the natural and synthetic fibers from sugar palm yarn fiber and glass fiber, respectively, with total reinforcement of 30 and 40 wt %. Then, the ratio of reinforcement between the sugar palm yarn fiber and woven glass fiber was selected at 70/30, 60/40 and 50/50, respectively. The tensile, flexural, impact and compression properties of the treated sugar palm hybrid composites were studied and compared with the previous study (untreated sugar palm yarn fiber hybrid composites) in order to recommend the optimum hybrid composite for various structural applications.

EXPERIMENTAL PART

Materials

In this research, the main material used as reinforcement was sugar palm fiber which was purchased from Hafiz Adha Enterprise at Kampung Kuala Jempol, Negeri Sembilan, Malaysia. A woven E-glass fiber (210 g/m^2) was supplied by Sky Tech Malaysia Sdn. Bhd. Unsaturated polyester resin (RTM grade, 40% styrene content, density of 1.025 g/cm^3) were purchased from CCP Composites Resins Malaysia Sdn. Bhd, methyl ethyl ketone peroxide (MEKP) (Butanox-M50) as a curing initiator were purchased from AkzoNobel China and cobalt(II) naphthenate as a reaction accelerator were purchased from Sigma Aldrich (M) Sdn. Bhd. Sodium hydroxide (NaOH) pellets were purchased from Merck (M) Sdn Bhd.

Alkaline treatment

The bundles of sugar palm fiber were soaked in a 1% NaOH solution or 0.25 M for 1 hour [19]. The treated sugar palm fibers were then washed several times with distilled water until pH 7 was obtained. Subsequently, the fibers were dried in an oven at 60 °C for 24 hours. Then, the chemical constituents (Table 1) of the untreated and treated sugar palm fiber were analyzed according to the following standard methods: ethyl-benzene extractive (TAPPI T 204 CM-97), lignin (TAPPI T 222 OM-98), holocellulose [20] and alfa cellulose (TAPPI T 203 CM-99). Table 1 shows also the tensile properties of untreated and treated single sugar palm fiber [21].

Spinning process

In order to ensure producing a high degree of regularity of sugar palm yarn fiber firstly, the raw of sugar palm fiber in a bundle form (Fig. 1a) was combed (Fig. 1b) to align the fibers and remove the shortest elements. For each piece of 2500 tex of sugar palm yarn fiber, the sugar palm fiber was constantly weighed using weighing balance and aligned to 0.5/0.2 g/m. The tex of sugar palm yarn fiber was measured using Eq. (1) in accordance to ASTM D1907.

$$\text{Linear density (Tex)} = w \cdot \text{K}/l = (0.5 \cdot 1000)/0.2 = 2500 \text{ tex} \quad (1)$$

where: w – an average weight of yarn (g), K – a constant value (1000 m/g) for tex, l – a length of the yarn (m).

T a b l e 1. Chemical constituents and tensile properties of untreated and treated sugar palm fibers

Chemical constituents	Composition, wt %	
	Untreated	Treated
Cellulose	47.74	54.39
Hemicellulose	5.96	5.01
Lignin	37.68	31.30
Tensile properties		
Tensile strength, MPa	156.96	332.28
Tensile modulus, GPa	4.96	17.27
Elongation at break, %	7.98	5.30

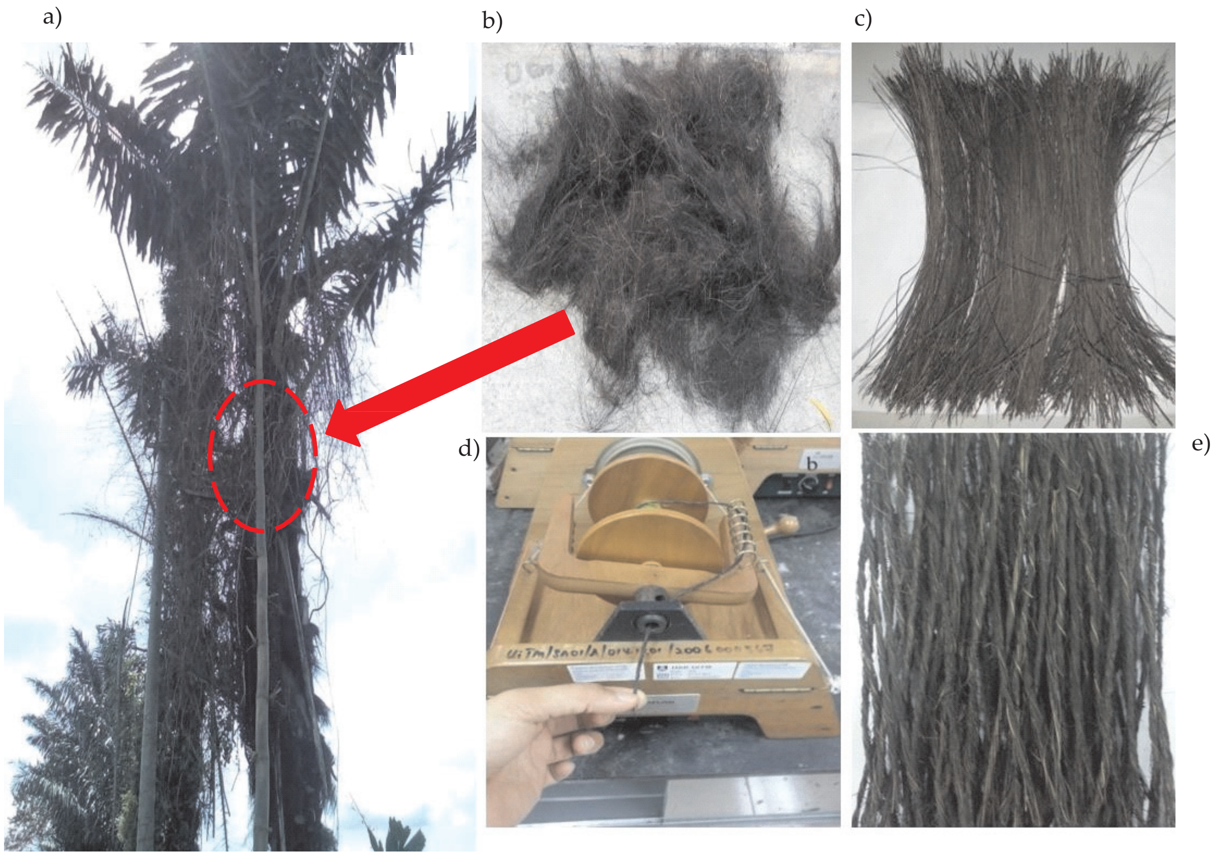

Fig. 1. a) Sugar palm tree, b) bundle of sugar palm, c) bundle of sugar palm fiber after combing, d) yarning process, e) sugar palm yarn fiber with 2500 tex [22]

Then, a manual spinning machine from SDL ATLAS (Fig. 1c) with a speed of 1000 rpm/pc of sugar palm fiber was used to make a yarn fiber with a *Z*-twist direction (Fig. 1d).

Fabrication of composites

As resulted from the previous study, the mechanical properties increased linearly from 10 to 40 wt % [23]. Hence, for the fabrication of hybrid composites, the ratio between matrix and reinforcement was selected at 70/30 wt % and 60/40 wt %, respectively. The ratio of the sugar palm yarn fiber to glass fiber was selected at 70/30, 60/40 and 50/50, respectively. A certain amount of glass fibers was placed inside the mold, followed by a placement of all the quantity of sugar palm fiber and finally the rest of glass fiber. After each placement, a small amount of mixed unsaturated polyester resin was poured over the fibers in order to improve the absorption of resin and to minimize the formation of voids and finally compressed using hot press machine with at 70 °C and 8 MPa for 30 minutes [21]. Table 2 shows the summary of the formulation of hybrid composites between the matrix and fibers. Figure 2 shows the layup segmentation between layers for hybridization of sugar palm yarn fiber with glass fiber.

Methods of testing

– The tensile test was performed using an Instron 3365 test machine according to ASTM D3039. The dimensions of the samples were 150 × 15 × 3 mm. The gauge length

T a b l e 2. Formulation of hybrid composites between matrix, sugar palm yarn fiber and woven glass fiber

Matrix compositions, wt %	Fiber compositions, wt %	Breakdown sugar palm fiber : glass fiber, wt %/wt %	Reinforcement layout
70	30	70 : 30 (21 : 9)	2 plies of GF/SPF/2 plies of GF
		60 : 40 (18 : 12)	3 plies of GF/SPF/2 plies of GF
		50 : 50 (15 : 15)	3 plies of GF/SPF/3 plies of GF
60	40	70 : 30 (28 : 12)	3 plies of GF/SPF/2 plies of GF
		60 : 40 (24 : 16)	3 plies of GF/SPF/3 plies of GF
		50 : 50 (20 : 20)	4 plies of GF/SPF/4 plies of GF

GF – glass fiber; SPF – sugar palm fiber.

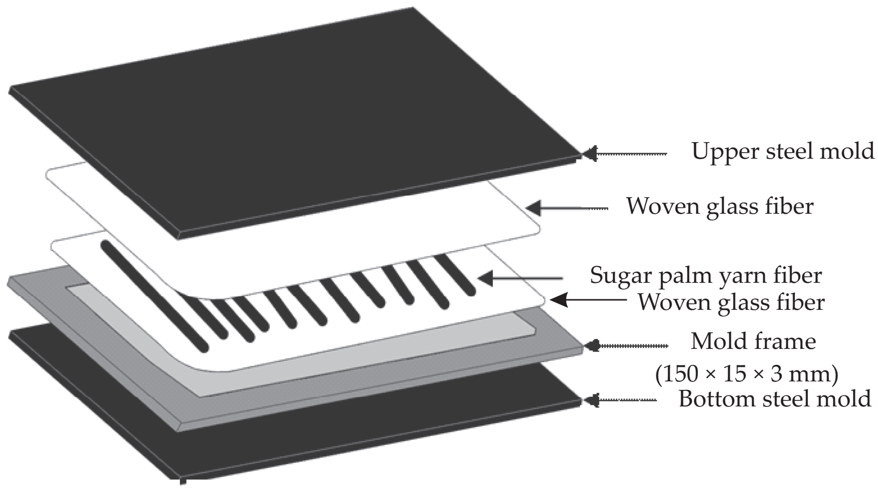

Fig. 2. Schematic diagram of layup segmentation of hybrid composites

was 60 mm, with a crosshead speed of 5 mm/min applied for the test. The tensile modulus (experimental value) extracted from the tensile test results can be compared with the tensile modulus (theoretical value) from the rules of mixture (ROM) theory calculation. From the ROM theory in Eq. (2), an approximate composite modulus (E_c) can be obtained from a modified ROM equation as follows, while Eq. (3) refers to the formulation of the volumetric fraction of the matrix and Eq. (4) refers to the formulation of the volumetric fraction of the fiber.

$$Ec = \eta_0 E_f V_f + E_m V_m \quad (2)$$

$$V_m = (\text{mass of matrix/density of matrix})/ [(\text{mass of matrix + mass of fiber})/ (\text{density of matrix + density of fiber})] \quad (3)$$

$$V_f = (\text{mass of fiber/density of fiber})/[(\text{mass of matrix + mass of fiber})/(\text{density of matrix + density of fiber})] \quad (4)$$

where: η_0 refers to the Krenchel factor or efficiency factor, and the value differs according to the fiber orientation. The terms E_f and E_m refer to the modulus of the fiber and matrix respectively, while V_f and V_m refers to the volume fraction of the fiber and matrix, respectively [refer to Eq. (3) and Eq. (4)]. According to Aziz and Ansell [24], the η_0 for unidirectional (0°) fiber is equal to 1 and for the woven glass fiber (0/90°) the orientation is 0.5.

– A flexural test was performed by the three-point bending method using an Instron 3365 test machine according to ASTM D790. The dimensions of the samples were 127 × 13 × 3 mm. The crosshead speed was set at 5 mm/min and a support span-to-depth ratio is 16 : 1.

– An Izod impact test was performed using an Instron CEAST 9050 testing machine with a capacity of the pendulum of 5.5 J according to ASTM D256. The dimensions of the unnotched samples were 65 × 10 × 30 mm. The velocity of the striking nose at the moment of impact was 3.5 m/s.

– Compression testing was carried out using an Instron 3366 testing machine with a 10 kN load-cell at room temperature. The testing procedures were carried out accordance with ASTM D3410. The cross-head speed used was 5 mm/min and the dimensions of the samples were 120 × 10 × 3 mm.

RESULTS AND DISCUSSION

Tensile properties

The average tensile strength, elongation at break and tensile modulus of the developed hybrid composites are shown in Fig. 3. The results indicated that the composites with 40 wt % of treated sugar palm yarn fiber exhibited higher strength values compared to those containing 30 wt % of untreated and treated sugar palm yarn fiber hybrid composites and those with 40 wt % of untreated sugar palm yarn fiber hybrid composites (Fig. 3a). The highest tensile strength of 89.90 MPa was achieved at 40 wt % with 50/50 fiber ratio.

This was mainly due to the better interfacial adhesion between the fibers and the matrix resulting in a higher load carrying capacity and transferring the load matrix to the fiber [25]. The elongation at break quantifies the flexibility of a composite. The elongation at break graph in Fig. 3b shows that the trend for the composites decreased with an increasing ratio of glass fibers for both the 30 wt % and 40 wt % of fiber loading. Among the hybrid composites, those containing sugar palm/glass fiber at 70/30 ratio exhibited the highest elongation at break, whereas the composites with a 50 : 50 ratio of sugar palm to glass fiber were found to have the lowest values of this property.

This phenomenon was possibly due to the fact that the elongation at break of glass fiber (0.5%) [27] was lower than that for treated sugar palm fiber (5.3%). Thus, sug-

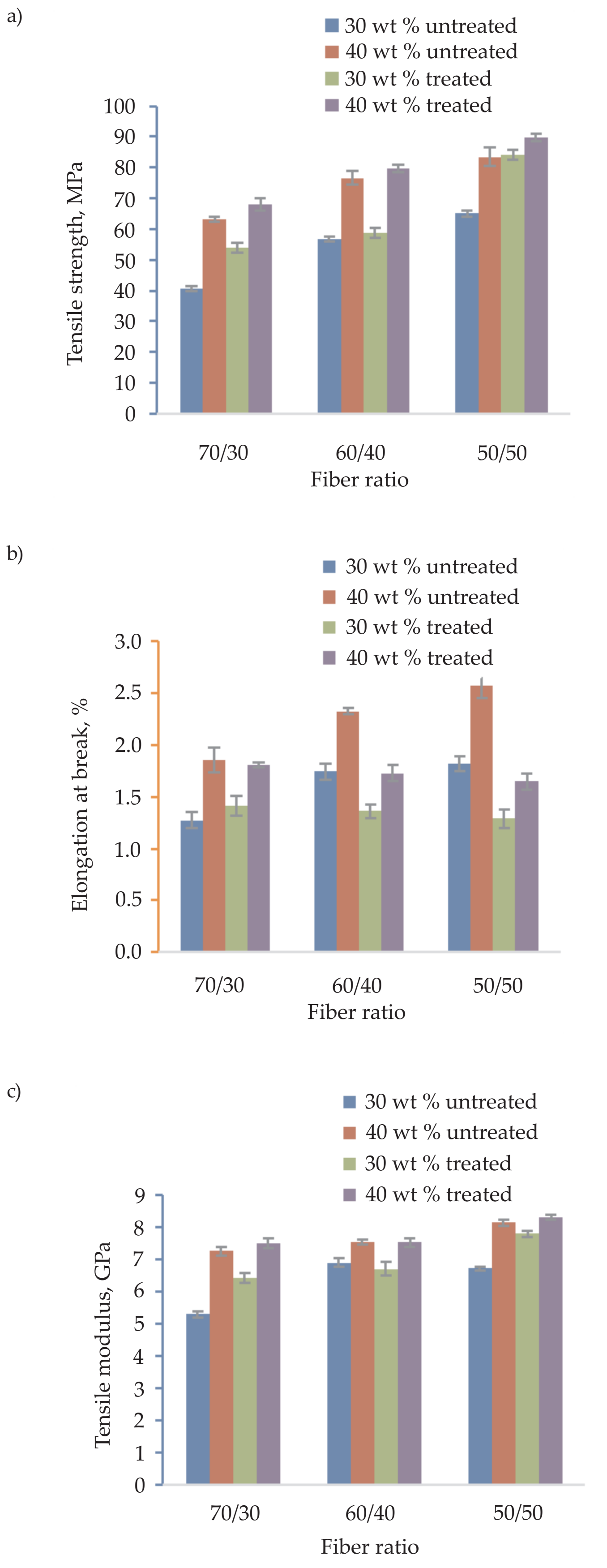

Fig. 3. Tensile properties of untreated [26] and treated sugar palm yarn fiber hybrid composites: a) tensile strength, b) elongation at break, c) tensile modulus

ar palm yarn fiber had a higher strain to failure characteristic compared to the low strain of extensibility of glass fiber. The observed decrease in flexibility through the decreasing elongation at break of the composites was likely related to the high stiffness of the composites with an increasing tensile modulus. Other than the improvement of tensile properties due to the increase of glass fiber loading, an effective alkaline treatment of the sugar palm fiber also improved the tensile properties of the composites. As shown in Fig. 3c, the hybrid composite with 40 wt % treated sugar palm yarn fibers gave superior tensile and modulus property values compared to the untreated yarn fiber hybrid composites. This may be due to the improvement of interfacial bonding between the treated sugar palm yarn fiber with glass fiber surface and the matrix after the removal about 16.93% of lignin (Table 1).

An improvement of the interfacial bonding of the treated sugar palm yarn fiber compared to the untreated fiber was attributed to the removal of impurities and waxy substances from the fiber surface and the creation of a rougher surface after the alkaline treatment (Fig. 4). The alkaline treatment cleaned the surface of the fibers of impurities and waxy substances, which in turn increased the disruption of the moisture absorption process by removing the coating of the hydroxyl groups in the fiber, thus, increasing the interface surface quality [28]. In addition, the enhancement in the tensile strength and modulus of the treated sugar palm yarn fiber hybrid composites after the alkaline treatment in the studies may be attributed to a phenomenon called fibrillation. The untreated fibers are packed together in a bundle. After the fiber treatment, the packed alignments of the fibers are broken into the smaller groups through the dissolution of about 15.94% hemicellulose (Table 1). This phenomenon increases the effectiveness of the surface area available for contact and matrix penetration inside the fiber cell, thus improving interfacial adhesion [29, 30].

In this theory, the composite efficiency factor or Krenchel factor is different where it is based on the number of layers of the fiber and fiber orientation. For determining the properties of unidirectional (0°) orientation fibers and hybrids with woven glass fiber (0/90°) fiber orientation, the composite efficiency would be 1 and 0.5, respectively [31]. Since it is a hybrid composite with two parts of glass fiber and one part of sugar palm yarn fiber as in Fig. 2, the calculation of the Krenchel factors are as follows: $\eta_0 = (1/3 \cdot 1) + (2/3 \cdot 0.5) = 1/3 + 1/3 = 0.67$

Equation 2 shows an example of calculation for 30 wt % of fiber reinforcements with a fiber ratio of 70/30. The E_f (sugar palm) = 4.96 GPa, E_f (glass fiber) = 70 GPa [27, 32], E_m = 3.54 GPa. Hence, the theoretical modulus for the composites is: $E_c = \eta_0 E_f V_f + E_m V_m = 0.67\ [(1/3 \cdot 4.96) + (2/3 \cdot 70)] \cdot 0.3089 + 3.54 \cdot 0.6911 = 12.45$ GPa.

The theoretical values of the tensile modulus calculated using Eq. (2) were compared with the experimental values as in Fig. 3. The results presented in Table 3

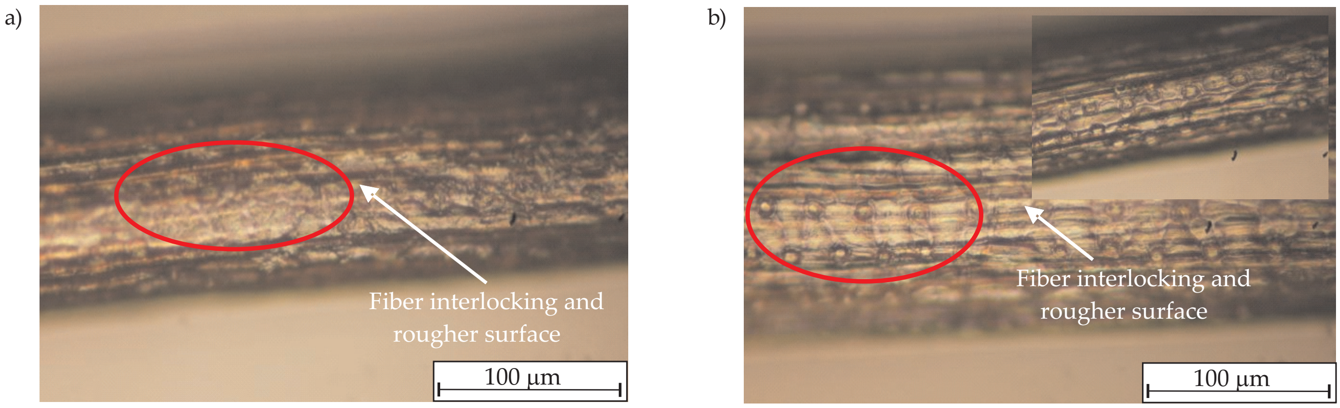

Fig. 4. Surface morphology of: a) untreated, b) treated single sugar palm fiber

T a b l e 3. Comparison of experimental tensile modulus and theoretical values calculated from the rules of mixture (ROM) for hybrid composites

Designation of fibers	Fiber ratio wt %	Experimental GPa	Theoretical GPa
30 wt % Untreated	70/30	5.29	13.41
	60/40	6.88	12.79
	50/50	6.70	12.41
40 wt % Untreated	70/30	7.24	17.49
	60/40	7.52	16.54
	50/50	8.12	15.11
30 wt % Treated	70/30	6.42	12.45
	60/40	6.70	12.37
	50/50	7.78	12.29
40 wt % Treated	70/30	7.49	15.37
	60/40	7.52	15.28
	50/50	8.28	15.19

show that the theoretical value of tensile modulus decreased as the glass fiber ratio increased and this showed a contradicting trend from the non-hybrid composite samples. This might be because the elongation value of the fiber does not take into account the equation. From the experimental findings, the elongation of sugar palm is 5.3%, while that of glass fiber is 0.5%, meaning that the sugar palm fiber is more flexible than glass fiber. As the glass fiber ratio loadings increased, the flexibility of the composites decreased and the modulus of the composites increased. This means that the brittleness of the composites increased as the elongation of the composites decreased.

Besides that, the improvement of surface quality and hydrophobicity of sugar palm yarn fiber resulted in a better compatibility with the glass fiber and the matrix. This is because after alkaline treatment, the treated sugar palm yarn fiber (with increased hydrophobic properties) and glass fiber (hydrophobic in nature) can be considered have similar hydrophobic attraction. Then the remaining reactive sites (hydroxyl groups) of the glass fibers can easily make strong hydrogen bonds (-H) with the ester and carboxylic (C=O-OH) groups of unsaturated polyester. In addition, effect of fibrillation of treated sugar palm fiber leads to a better interfacial adhesion and matrix penetration into the sugar palm fiber structure. Finally it gave a synergistic effect to other mechanical properties of the composites.

Flexural properties

From Fig. 5, it is evident that at 30 wt % and 40 wt % fiber loadings as the glass fiber loading ratio increased, the flexural strength and flexural modulus also increased. This was because of the increase in the stiffness due to consolidation of compaction between the glass fibers as a skin layer, sugar palm yarn fibers as a core and the matrix in resisting three-point bending forces. Further, the original properties of glass fibers include a high modulus of 70 GPa compared to that of sugar palm fiber which would be around 0.5 to 3.37 GPa. The glass fibers as a skin layer provide reinforcement to the composites. This reinforcement may occur through a mechanism, in which the applied stress is transferred from one segmentation layer to the next, thereby enabling an even and efficient distribution of the stress throughout the material.

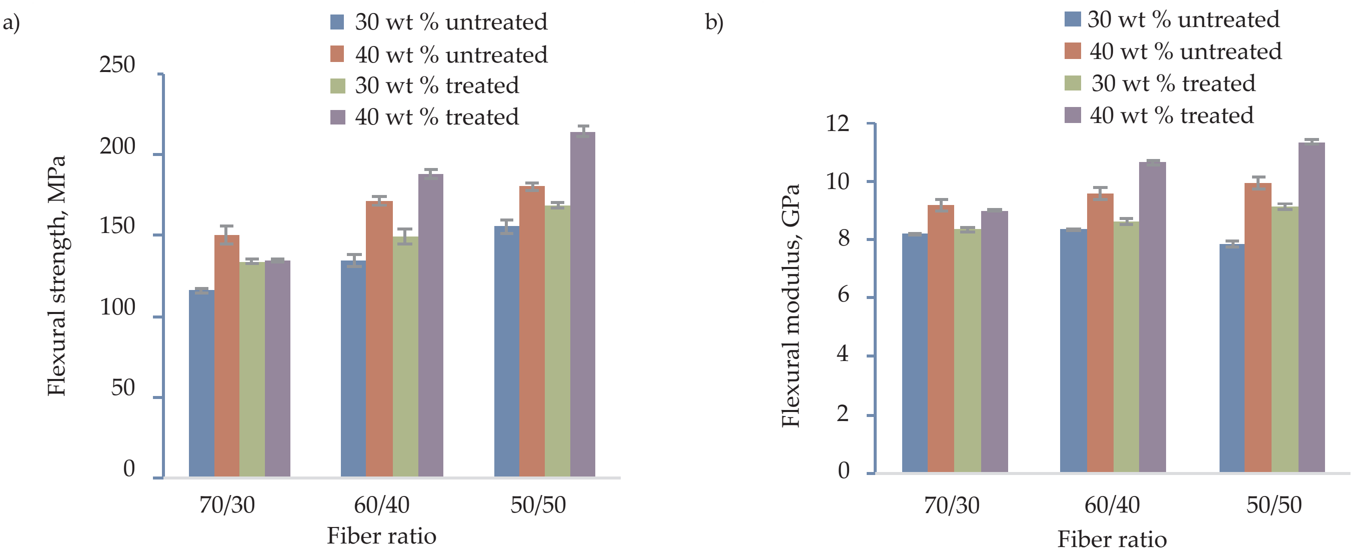

Fig. 5. Flexural properties of untreated [26] and treated sugar palm yarn fiber hybrid composites: a) flexural strength, b) flexural modulus

As depicted in Fig. 5, the flexural strength and modulus of the hybrid composites have similar trends as the tensile properties. The flexural properties increases with the addition of glass fiber. In flexural test, failures mainly occurred due to bending and shearing [33]. The increased flexural strength of the hybrid composites with the loading of glass fiber was mainly due to the increased resistance to shearing of the composites. The rigid glass fiber effectively acted as a skin layer for the composites. In addition, a further increase of glass fiber content in the hybrid composites resulted in the composite having sufficient modulus.

From both fiber loadings of 30 wt % and 40 wt %, the highest fiber loading was achieved at 50 : 50 ratio of sugar palm yarn fiber and glass fiber. This was due to the fibers which were present in a sufficient amount, providing an effective stress transfer between the matrix and fiber and also due to the inherent properties of glass fiber. This suggested that the flexural properties of the composites were more dependent on the amount of glass fiber rather than sugar palm yarn fiber, which may be due to the high modulus of the glass fiber (70 GPa) compared to sugar palm fiber (0.5 to 3.37 GPa) [34].

Comparing the untreated and treated sugar palm yarn fiber composites at various fiber loadings, the treated fiber composites showed better results for flexural strength and modulus. When compared with the untreated fiber composites, the alkaline treated composites recorded an 18.6% increase in flexural strength and a 13.9% increase in flexural modulus at 40 wt % of fiber loading for the 50/50 fiber ratio. The remarkable increase in flexural strength and modulus of the treated sugar palm yarn fiber hybrid composites was mainly due to the increased resistance to shearing of the composites as a result of the inclusion of an increased interface due to effective surface area available for wetting by the matrix [35].

Impact properties

The results from an impact test of the hybrid composites are shown in Fig. 6. In both untreated and treated sugar palm yarn hybrid composites for 30 wt % and 40 wt % content, the impact strength was found to have increased with an increase in the glass fiber loading up to the 50/50 fiber ratio. The impact strength of the treated sugar palm yarn hybrid composites with 40 wt % fiber loading at 50/50 of fiber ratio was higher with a value of 71.63 kJ/m^2 compared to other hybrid formulations. The impact resistance for this formulation showed 27.5% higher or better than the untreated sugar palm yarn fiber hybrid composites with the same fiber loading at 40 wt %. These values were contributed by the fibers which were

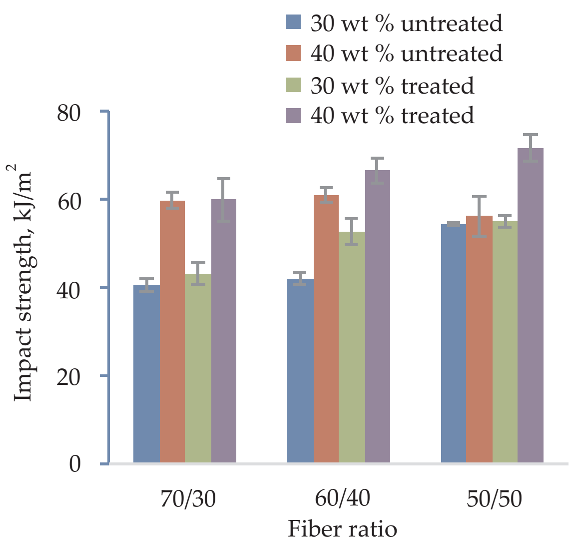

Fig. 6. Impact strength of untreated and treated sugar palm yarn fiber hybrid composites

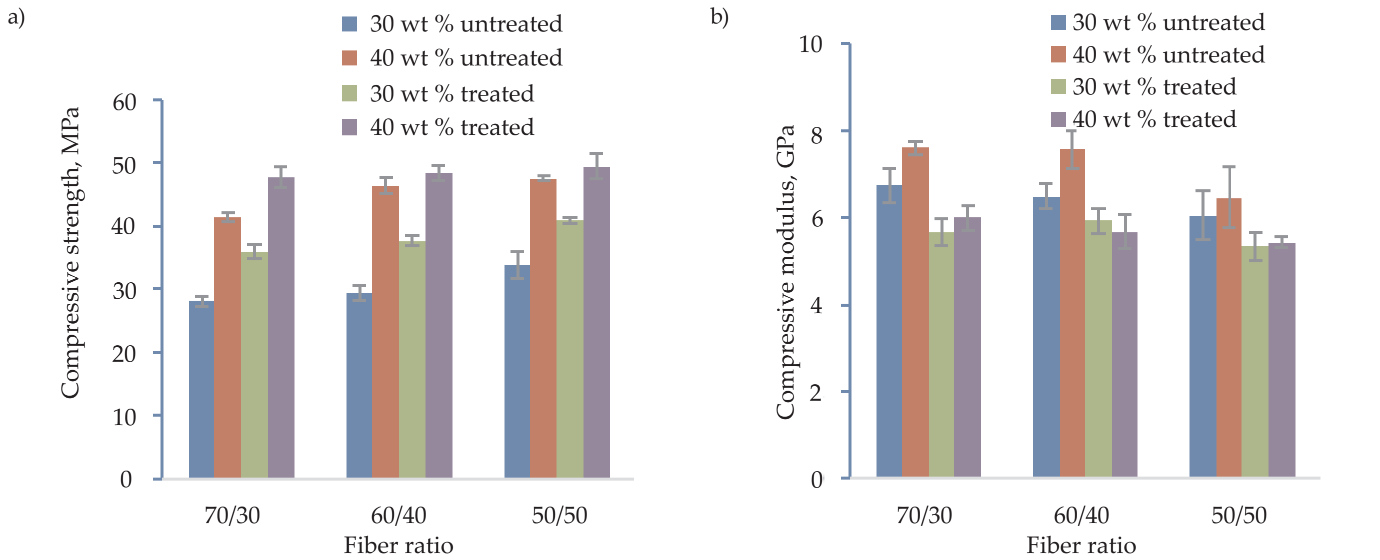

Fig. 7. Compression properties of untreated [26] and treated sugar palm yarn fiber hybrid composites: a) compressive strength, b) compressive modulus

present in sufficient amounts that could provide an effective stress transfer for the fiber and the matrix.

Impact response of natural fiber composites is highly influenced by the interfacial bond strength, the matrix and the fiber itself [5]. Fiber fracture dissipates less energy compared to fiber pull-out. The former is common in the composites with a strong interfacial bond while the occurrence of the latter is a sign of a weak bond [33]. As depicted in Fig. 6, by increasing the glass fiber ratio in the sugar palm yarn fiber composites, the impact strength of the untreated and treated hybrid composites increased from almost 6 to 32%. Better impact strength was observed from treated fiber hybrid composites (Fig. 6). These results were due to the high energy absorption capability of the supported glass fiber in the composite structure and effect of the fiber treatment that leads to better interfacial adhesion and bonding strength between the sugar palm fiber, glass fiber and the matrix itself.

Furthermore, when the hybrid composites were impacted, the glass fiber was able to resist the high impact load and, with the addition of better interfacial adhesion of fibers, finally was able to absorb a significant amount of the impact energy. Thus, the energy needed to initiate and propagate a crack increased. In composite systems, the structure of the fibers and fiber orientation plays an important role in the impact resistance of the composite as the fibers interact with the crack formation in the matrix and act as a stress transference medium. The high bonding quality due to the modification of the sugar palm fiber with glass fiber and matrix created a good interfacial region. Thus, it resulted in an improvement in the ability of the composite structure to absorb energy during crack propagation and enhanced the impact resistance of the hybrid composites [36].

Compression properties

The compressive strength and modulus of the hybrid composites are shown in Fig. 7. As depicted in Fig. 7, the compressive strength increased as the fiber loading increased from 30 to 40 wt % and also increased with an increase in glass fiber loading. However, the compressive modulus showed a reduction in modulus for both fiber loadings. The highest values of compression strength were achieved at 40 wt % of treated sugar palm yarn hybrid composites at a 50/50 fiber ratio at 49.27 MPa and the highest compressive modulus was exhibited by a sample with 40 wt % of untreated sugar palm yarn hybrid composite at a 70/30 fiber ratio at 7.6 GPa.

The treated hybrid composite shows lower compressive modulus than the untreated fiber hybrid composites. This is related to the dissolution of amorphous parts of hemicellulose and lignin in the fiber structure. This is because after the alkaline treatment the sugar palm fiber may indicate an improvement in the crystallinity index of hard cellulose due to the removal of the hemicellulose [37] and lignin (Table 1), which led to better packing of the cellulose chains. A better packing of hard cellulose chains, therefore, causes a decrease in the spiral angle and an increase in the degree of molecular orientation. After the alkaline treatment, the rearrangement of hard cellulose chains (fibrillation effect) towards the tensile force makes the cellulose chains to be more effective to maintain the stability and the stiffness of the fiber system [38].

However, in a compression test the specimens were forced to shorten and the materials tended to spread in the lateral direction (opposite direction with tensile force), hence the cross-sectional areas were increased until they reached failure or buckling. With shearing in process, the

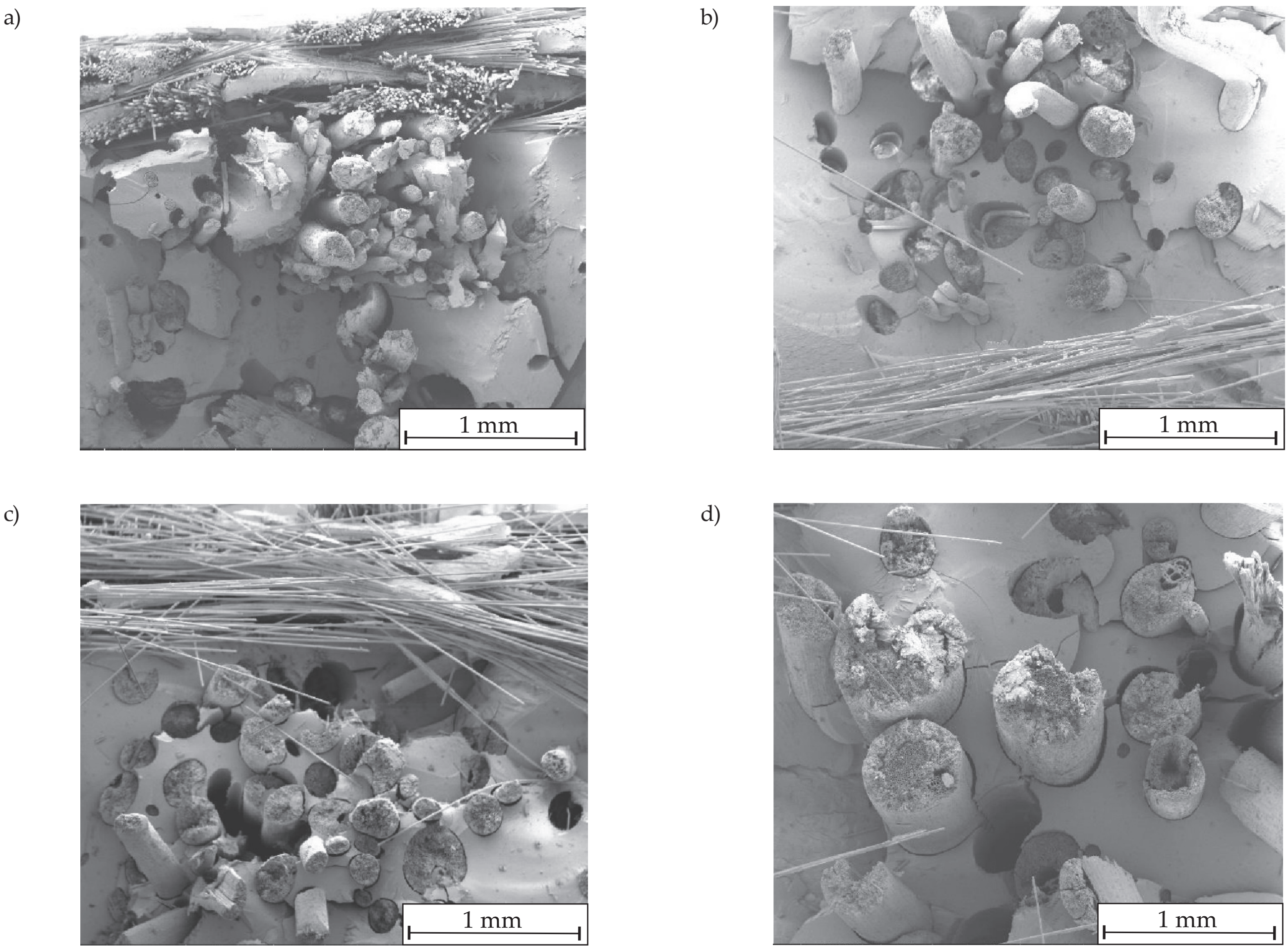

Fig. 8. SEM image of tensile fracture surface of: a) untreated 30 wt % (50 : 50), b) untreated 40 wt % (50 : 50), c) treated 30 wt % (50 : 50), d) treated 40 wt % (50 : 50) of sugar palm yarn fiber hybrid composites

untreated sugar palm yarn fiber (core) acted as a tendon which contains more amorphous parts from the lignin and hemicellulose structure (Table 1). Therefore it effectively maintained the stability of the composites in relation to shortening and spreading from the lateral direction compared with the treated sugar palm fibers. Hence the dissolution of hemicellulose and lignin had given the negative effect towards the compressive modulus due to different force applied to the composite systems.

Figure 8 shows the SEM image analysis of the tensile fracture surface of the untreated and treated sugar palm yarn fiber hybrid composites. It was found that the treated fiber hybrid composites (Fig. 8c and 8d) showed less matrix cracking and fiber debonding, which may be contributed to higher stress absorption resulting in higher tensile, flexural, impact and compression properties (as shown in Figs. 3, 5, 6, 7). When the hybrid composites were in tension, the glass fibers were able to resist the high tension and were also able to absorb a significant amount of tensile stress through the delamination of the glass fiber, fiber breakage and fiber pull-out of the sugar palm fiber.

Thus, the stress needed to initiate and propagate a crack increased. Moreover, the delamination at the glass fiber layer interface further contributed to additional stress dissipation into the core of the hybrid composites through the microcracks and finally reached the point of fiber breakage in the sugar palm fiber. It was observed that there is a reduction of holes in the fracture surface of the treated fiber hybrid composites compared to the untreated fiber hybrid composites in Fig. 8a and Fig. 8b. This might be due to good interfacial bonding between the sugar palm fibers with the matrix and hence the fiber pull out was minimized.

According to Abdul Khalil *et al*. [36], frictional losses as fibers were pulled out of the matrix were major contributors to the observed tensile properties of the glass fiber layer. This was due to the surface smoothness and regular cross-section of glass fiber. Furthermore, it is well known that fiber pull-out absorbs more stress than fiber breakage, where fiber fracture in these hybrid composites is of an elastic-plastic nature.

In fiber reinforced hybrid composites, the fibers play an important role in the tensile resistance of the composite, as they interact with the crack formation in the matrix and act as a medium for the stress transfer mechanism to occur. The better interfacial shear stress between the glass fibers with the matrix creates a good interfacial medium as can be seen in Figure 8. Additionally, the superior mechanical properties of glass fiber, as the glass fiber ratio increased, resulted in an improvement in the ability of the composite system to absorb stress during the ultimate tension and during the fracture propagation. This leads to the enhancement of the tensile resistance of the hybrid composites.

CONCLUSIONS

It was observed that the incorporation of both sugar palm yarn and glass fiber at 50 : 50 fiber ratio into unsaturated polyester matrix has resulted in an increase in the tensile strength, tensile modulus, flexural properties, impact properties and compressive strength. All the mechanical properties showed improvement after the alkaline treatment of sugar palm yarn fibers compared with the untreated hybrid composites, which was due to a better compatibility and balance ratio of the pack arrangement between the sugar palm yarn fiber and glass fiber with the matrix. Thus, this become an indication to combine the sugar palm with glass fiber and to treat the sugar palm fiber in order to produce hybrid composites of outstanding mechanical performance, renewable and of lower cost.

ACKNOWLEDGMENTS

The authors wish to thank Universiti Putra Malaysia (UPM), for providing research grants (GP-IPB), project number GP-IPB/2014/9441502 and excellent facilities. Thanks also to Faculty of Applied Sciences (FSG), Universiti Teknologi MARA (UiTM) Shah Alam for the excellent facilities and cooperation.

REFERENCES

[1] Yong C.K., Ching Y.C., Chuah C.H., Liou. N.S.: *BioResources* **2015**, *10*, 2597. http://dx.doi.org/10.15376/biores.10.2.2597-2608

[2] Ilyas R.A., Sapuan S.M., Mohd Nurazzi N. *et al.*: "Seminar Enau Kebangsaan", Bahau, Negeri Sembilan, Malaysia, 2019, pp. 2–11.

[3] Sahari J., Sapuan S.M., Zainudin E.S., Maleque M.A.: *Materials* & *Design* **2013**, *49*, 285. http://dx.doi.org/10.1016/j.matdes.2013.01.048

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

[5] Wambua P., Ivens J., Verpoest I.: *Composites Science and Technology* **2003**, *63*, 1259. http://dx.doi.org/10.1016/S0266-3538(03)00096-4

[6] Ahmad I., Baharum A., Abdullah I.: *Journal of Reinforced Plastics and Composites* **2006**, *25*, 957. http://dx.doi.org/10.1177/0731684406065082

[7] Shalwan A., Yousif B.F.: *Materials* & *Design* **2013**, *48*, 14. http://dx.doi.org/10.1016/j.matdes.2012.07.014

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

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

[10] Reddy V.G., Naidu V.S., Rani S.T.: *Journal of Reinforced Plastics and Composites* **2008**, *27*, 1789. http://dx.doi.org/10.1177/0731684407087380

[11] Nor A.F.M., Sultan M.T.H., Jawaid M. *et al.*: *BioResources* **2018**, *13*, 4404. http://dx.doi.org/10.15376/biores.13.2.4404-4415

[12] Aslan M., Tufan M., Kucukomeroglu T.: *Composites Part B: Engineering* **2018**, *140*, 241. http://dx.doi.org/10.1016/j.compositesb.2017.12.039

[13] AlMaadeed M.A., Kahraman R., Khanam P.N., Madi N.: *Materials* & *Design* **2012**, *42*, 289. http://dx.doi.org/10.1016/j.matdes.2012.05.055

[14] Nunna S., Chandra P.R., Shrivastava S., Jalan A.K.: *Journal of Reinforced Plastics and Composites* **2012**, *31*, 759. http://dx.doi.org/10.1177/0731684412444325

[15] Saba N., Tahir P.M., Jawaid M.: *Polymers* **2014**, *6*, 2247. http://dx.doi.org/10.3390/polym6082247

[16] Bharath K.N., Sanjay M.R., Jawaid M. *et al.*: *Journal of Industrial Textiles* **2018**, 1528083718769926. http://dx.doi.org/10.1177/1528083718769926

[17] Jaszewski J., Zajchowski S., Tomaszewska J., Mirowski J.: *Polimery* **2018**, *63*, 109. http://dx.doi.org/10.14314/polimery.2018.2.4

[18] Atiqah A., Maleque M.A., Jawaid M., Iqbal M.: *Composites Part B: Engineering* **2014**, *56*, 68. http://dx.doi.org/10.1016/j.compositesb.2013.08.019

[19] Bachtiar D., Salit M.S., Zainuddin E.S. *et al.*: *BioResources* **2011**, *6*, 4815. http://dx.doi.org/10.15376/biores.6.4.4815-4823

[20] Wise L.E., Murphy M., Addiecs A.A.D.: *Paper Trade Journal* **1963**, *122*, 35.

[21] Nurazzi N.M., Khalina A., Sapuan S.M. *et al.*: *Journal of Mechanical Engineering and Sciences* **2017**, *11*, 2650. http://dx.doi.org/10.15282/jmes.11.2.2017.8.0242

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

[23] Norizan M.N., Abdan K., Salit M.S., Mohamed R.: *Journal of Physical Science* **2017**, *28*, 115. http://dx.doi.org/10.21315/jps2017.28.3.8

[24] Aziz S.H., Ansell M.P.: *Composites Science and Technology* **2004**, *64*, 1219. http://dx.doi.org/10.1016/j.compscitech.2003.10.001

[25] Thiruchitrambalam M., Alavudeen A., Athijayamani A. *et al.*: *Materials Physics and Mechanics* **2009**, *8*, 165.

[26] Nurazzi N.M., Khalina A., Sapuan S.M., Rahmah M.: *Materials Research Express* **2018**, *5*, 045308. http://dx.doi.org/10.1088/2053-1591/aabc27

[27] Koronis G., Silva A., Fontul M.: *Composites Part B: Engineering* **2013**, *44*, 120. http://dx.doi.org/10.1016/j.compositesb.2012.07.004

[28] Khan R.A., Khan M.A., Zaman H.U. *et al.*: *Journal of Reinforced Plastics and Composites* **2010**, *29*, 1078.

http://dx.doi.org/10.1177/0731684409103148
[29] Vilay V., Mariatti M., Mat Taib R., Todo M.: *Composites Science and Technology* **2008**, *68*, 631. http://dx.doi.org/10.1016/j.compscitech.2007.10.005
[30] Mohd Nurazzi N., Khalina A., Ilyas R.A.: "Seminar Enau Kebangsaan", Bahau, Negeri Sembilan, Malaysia, 2019, pp. 78–81.
[31] Harris B.: "Engineering Composite Materials", The Institute of Materials, London 1999.
[32] Mohanty A.K., Misra M., Hinrichsen G.: *Macromolecular Materials and Engineering* **2000**, *276*, 1. http://dx.doi.org/10.1002/(sici)1439--2054(20000301)276:1<1::aid-mame1>3.0.co;2-w
[33] Mohd Hanafee Z., Khalina A., Mohd Nurazzi N.: "Structural Health Monitoring of Biocomposites, Fibre-Reinforced Composites and Hybrid Composites" (Eds. Mohammad J., Mahamed T., Naheed S.), Woodhead Publishing 2019, 1. https://doi.org/10.1016/B978-0-08-102291-7.00001-0
[34] Li Y., Mai Y.W., Ye L.: *Composites Science and Technology* **2000**, *60*, 2037. http://dx.doi.org/10.1016/S0266-3538(00)00101-9
[35] Bachtiar D., Sapuan S.M. Hamdan M.M.: *Polymer Plastics Technology and Engineering* **2009**, *48*, 379. http://dx.doi.org/10.1080/03602550902725373
[36] Abdul Khalil H.P.S., Hanida S., Kang C.W., Nik Fuaad N.A.: *Journal of Reinforced Plastics and Composites* **2007**, *26*, 203. http://dx.doi.org/10.1177/0731684407070027
[37] Ilyas R.A., Sapuan S.M., Rushdan I. *et al*.: *Journal of Materials Research and Technology* **2019**. http://dx.doi.org/10.1016/j.jmrt.2019.04.011
[38] Rong M.Z., Zhang M.Q., Liu Y. *et al*.: *Composites Science and Technology* **2001**, *61*, 1437. http://dx.doi.org/10.1016/S0266-3538(01)00046-X

Received 11 III 2019.