Available online at www.sciencedirect.com

jmr&t Journal of Materials Research and Technology

journal homepage: www.elsevier.com/locate/jmrt

Original Article

Effect of reinforcement of Alkaline-treated sugar palm/bamboo/kenaf and fibreglass/ Kevlar with polyester hybrid biocomposites: mechanical, morphological, and water absorption properties

F.S.M. Radzi [a,b], M.J. Suriani [a,b,c,**], A. Abu Bakar [a,b], A. Khalina [c], C.M. Ruzaidi [a,b], WB Wan Nik [a], M. Awang [a], F. Zulkifli [a,b], S. Abdullah [a], R.A. Ilyas [c,d,e,f,*], Sayed M. Eldin [g,***]

[a] Faculty of Ocean Engineering Technology and Informatics, Universiti Malaysia Terengganu, 21030 Kuala Nerus, Terengganu, Malaysia
[b] Marine Materials Research Group, Faculty of Ocean Engineering Technology and Informatics, Universiti Malaysia Terengganu, 21030 Kuala Nerus, Terengganu, Malaysia
[c] Laboratory of Biocomposite Technology, Institute of Tropical Forestry and Forest Products, Universiti Putra Malaysia, UPM 43400, Serdang, Selangor, Malaysia
[d] Department of Chemical Engineering, Faculty of Chemical and Energy Engineering, Universiti Teknologi Malaysia UTM, 81310 Johor Bahru, Johor, Malaysia
[e] Centre for Advanced Composite Materials, Universiti Teknologi Malaysia UTM, 81310 Johor Bahru, Johor, Malaysia
[f] Centre of Excellence for Biomass Utilization, Universiti Malaysia Perlis, 02600, Arau, Perlis, Malaysia
[g] Center of Research, Faculty of Engineering, Future University in Egypt New Cairo 11835, Egypt

ARTICLE INFO

Article history:
Received 12 January 2023
Accepted 7 April 2023
Available online 13 April 2023

Keywords:
Sugar palm
Kenaf
Bamboo
Reinforcement
Composites
Natural fibre

ABSTRACT

In this age of globalisation, decreasing synthetic resources have exhilarated global communities to apply natural fibres as substitute materials for green technology development. The growth of products from lignocellulose fibre-reinforced composites has been a wide topic among material scientists and engineers due to their abundance, sustainability in nature, biodegradability, and availability at low cost. A series of natural/synthetic hybrid fibre-reinforced composites are prepared by reinforcing polyester resin as the matrix. Natural fibres such as sugar palm/kenaf/bamboo with fibreglass/Kevlar hybrid composite materials were used in this research to determine the mechanical and water absorption properties. The difference between the weight content of natural fibres which were 0 (control sample), 15, 45, and 60 wt% influenced their strength of mechanical properties. The Charpy impact and tensile test were performed following the ASTM D6110-10 and ASTM D3039, respectively. A water absorption test in accordance with ASTM D570-98 was also performed on three different natural fibre-reinforced hybrid composite materials to

* Corresponding author.
** Corresponding author.
*** Corresponding author.
E-mail addresses: surianimatjusoh@umt.edu.my (M.J. Suriani), ahmadilyas@utm.my (R.A. Ilyas), sayed.eldin22@fue.edu.eg (S.M. Eldin).
https://doi.org/10.1016/j.jmrt.2023.04.055

determine which composite had the best water resistance property. The results showed that hybrid fibre-reinforced composite for 45 wt% kenaf fibre possessed better tensile properties and 60 wt % sugar palm fibre performed better during the Charpy impact strength test compared to other natural/synthetic hybrid fibre-reinforced composites. It was concluded that sugar palm fibres demonstrated the best water resistance in this study.

1. Introduction

Composite materials are made up of two or more products, such as fibre and matrix. They are physically combined in order to achieve the advantages of both materials while overcoming the weaknesses of each element. Composite materials are becoming more popular as they replace traditional materials with cheaper, lighter, stronger, and tougher alternatives [1]. New composite material technology for aerospace, automotive [2], wastewater treatment [3,4], electrical conductive [5], medical [6] and high-performance industrial markets is demonstrated by advanced composites [7,8]. However, it is the least in the marine field, such as boat construction.

Natural fibre composites are environmentally friendly materials that have gained attention in the manufacturing sectors of automotive and construction in the last decade. As a result, many researchers' and manufacturing industries' focus have shifted to eco-friendly practices to reduce material costs while preserving the environment [9–11]. The shift from synthetic composite towards natural fibre composite has led to the creation of environmentally friendly products with biodegradable and renewable sources. The expansion of next-generation materials derived from renewable source materials is an expanding field of study. When non-renewable sources are no longer available to fulfil our needs in the upcoming century, these materials can be used as a substitute [12].

Natural fibres generally outperform synthetic and mineral fibres because of their low density, eco-friendliness, non-toxicity, renewability, bio-standardisation, relative non-abrasion, high specific strength and modulus, as well as ease of processing [13]. Despite their numerous benefits, natural fibres have a few drawbacks, including low strength, low modulus, high moisture uptake, and are easily combustible. To counter this problem, a hybridisation technique is being considered, which involves incorporating synthetic fibre reinforcement with natural fibres in a polymer matrix, leading to the formation of a hybrid composite. The hybridisation method allows for the modification of the composite's properties to suit the application. Throughout most cases, hybridisation is done to make a new class of material that maintains the benefits of its constituent materials while overcoming some of their constraints [14]. To increase the physical and mechanical properties, the hybridisation of the composite is introduced worldwide. Hybrid composite materials are gaining attention in many different industrial sections [15,16]. The hybridisation of natural and synthetic fibres is an excellent method for improving the mechanical properties and moisture resistance of the resulting hybrid composite [17]. The hybrid composite nowadays is highly recommended in many industries [18,19]. Recently, there has been an upsurge in global consumer interest in green material concerns that substitute entirely or partially synthetic fibre with natural fibre composites. The cost can be partially reduced by using Kevlar and fibreglass as a filler in the composites [20]. Based on previous reports, in comparison to single-fibre reinforcements, hybrid fibres in composites can withstand higher loads [21]. The use of two types of short fibres with different lengths and diameters in a single polymer matrix offers some advantages over using either of the fibres alone. The majority of researches are focused on the hybridisation of natural fibres with glass fibres to improve their properties [22].

Among the recently reported works on developing kenaf-glass (KG) fibres reinforced unsaturated polyester hybrid composite, it was found that using the sheet moulding compound process gives the highest effect on the mechanical properties. It obtained the highest flexural, tensile, and impact strengths from treated kenaf with 15/15 v/v kenaf/glass fibre hybrid composite [23]. Other researchers introduced the hybridisation between roselle fibre (RF)/sugar palm fibre (SPF)/thermoplastic polyurethane (TPU) hybrid composites, and it was shown that the hybridisation reduced the water absorption and increased the thermal properties of hybrid composites [9]. Another effort found that a combination of silica, liquid rubber, and epoxy was used to toughen epoxy/kenaf hybrid composite for potential automotive applications, and the mechanical properties exhibited the highest impact and flexural strengths to a certain extent [7]. Further studies on Kevlar/kenaf hybrid composites reported the composites fabricated with a ratio of 78/22 that exhibited better mechanical properties compared to other hybrid composites [24]. Another study on epoxy matrix composites reinforced by sisal/bamboo fibers by Chandramohan et al. [25], showed an increase in mechanical strength such as tensile and flexural properties. Another reported work described that the engineered bamboo scrimbers were prepared by impregnating bamboo bundles with phenol-formaldehyde (PF) resin that increased the mechanical properties. Thus, to extend its application, some bamboo-based products, such as plywood, laminated lumber, particleboard, and fibre-reinforced polymer composites are produced and widely used in many areas such as furniture, flooring, building, and civil engineering field [26].

From previous research, physical and chemical treatments, as well as combinations of the two, have been used to reduce the hydrophilicity of oil palm fibres [27]. These methods have been thoroughly researched by Essabir et al. [28], and Shinoj et al., [29]. Chemical treatment is widely used in manufacturing composites because of its effectiveness. Among the chemical treatments for natural fibres,

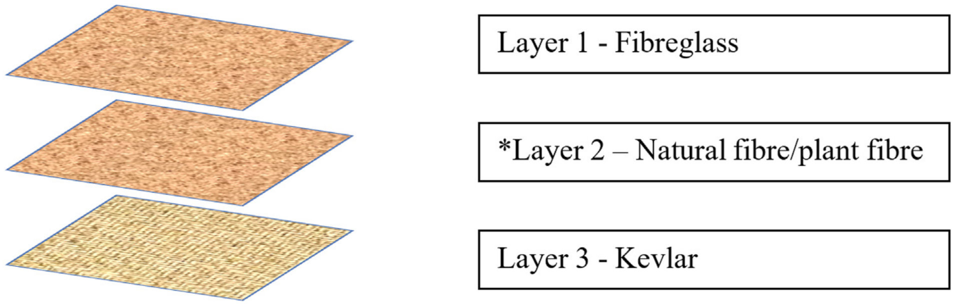

Fig. 1 – Layer of composites. * Natural fibres used are sugar palm/kenaf/bamboo fibres.

alkalinisation is one of the most cost-effective methods. It removes non-cellulosic materials that cover cellulose fibres and bind fibrils together, such as impurities, waxes, pectin, and hemicellulose. The removal of these substances results in a roughened fibre surface, which encourages surface contact. The effects enhance mechanical properties by promoting mechanical interlocking between polymers and fibres. Hydrothermal treatment, for example, has been used to modify fibre surfaces, improve compatibility between fibres and polymer matrices, and remove hemicellulose components [27]. Several efforts have been made to improve the interface between the hydrophilic bamboo fibre and the hydrophobic polymer matrix. A silanisation surface modification treatment was used to reduce the rate of water absorption in a bamboo-reinforced polyester composite. Prior to silane treatment, the bamboo fibres were mercerised to remove lignin and waxes from their surfaces [30]. Another study by Atiqah et al. [23], stated that to avoid high moisture absorption, the fibres were treated after encapsulation in plastic, followed by mercerisation with a 6% sodium hydroxide (NaOH) diluted solution.

In this study, the use of natural fibres (sugar palm/kenaf/bamboo) reinforced with fibreglass/Kevlar and polyester as the matrix was studied. The 0, 15, 45, and 60 wt% of natural fibres (sugar palm/kenaf/bamboo) hybrid with fibreglass/Kevlar were fabricated. The effects of different weight percentages of every natural fibre hybrid composite were investigated. The impact, tensile, and water absorption tests were analysed. The objectives of this research were to determine the physical and mechanical properties of three alternative natural fibres hybrid with fibreglass/Kevlar-reinforced polyester composite materials. This experiment showed the best weight content percentage of each natural fibre, showing the correlation of manufacturing defects that can affect the performance of physical and mechanical properties and investigating the interfacial adhesion between fibre-matrix. This fundamental study was carried out to develop a new green composite material in hull boat construction due to biodegradable materials and it is not widely used in the marine field.

2. Materials and methods

2.1. *Material preparation*

In this study, sugar palm and kenaf fibres were supplied by Hafiz Adha Enterprise (Industri Enau Malaysia) and Innovative Pultrusion Sdn. Bhd. Of Negeri Sembilan, Malaysia, while bamboo was supplied by Hangterra Bamboo Company. Synthetic fibres such as fibreglass (CSM 225) and Kevlar 29 were supplied by MSET Inflatable Composite Corporation Sdn. Bhd. Of Terengganu. The unsaturated polyester resin Reversol P-9509 as the matrix was also supplied by MSET Inflatable Composite Corporation Sdn. Bhd.

2.2. *Fabrication*

Firstly, the raw natural fibres which were sugar palm, kenaf, and bamboo fibres were treated with 6 wt% of NaOH solutions at room temperature for 3 h. After the treatment, the fibres were thoroughly washed with running water and allowed to dry at room temperature for 48 h. The fabrication of this natural/synthetic hybrid composite was prepared by using sugar palm, kenaf, and bamboo fibres, while polyester resin acted as the matrix. The samples were prepared by different weight percentage compositions of sugar palm, kenaf, and bamboo fibres hybrid with fibreglass/Kevlar polymeric composites such as 0, 15, 45, and 60 wt%. The hand layup technique in a steel mould was used to fabricate natural/synthetic hybrid composites. The samples were then cured for 24 h at room temperature. The ratio of resin and catalyst in this research was 1:5. The polyester and methyl ethyl ketone peroxide (MEKP) catalysts were mixed and thoroughly stirred for about 5 min to ensure that the mixture was well mixed before they were poured into the mould. The layer and designation of different natural fibre-reinforced (sugar palm/kenaf/bamboo) hybrid fibreglass/Kevlar composite materials for different weight compositions are illustrated in Fig. 1 and Table 1, respectively.

The provided mould measured 230 mm (length), 5 mm (thickness), and 160 mm (width). The fibres of sugar palm,

Table 1 – Designation of natural fibre-reinforced fibreglass/Kevlar hybrid composite materials.

Percentage of materials %	Designation of each percentage loading materials			
	0% (Control sample)	15%	45%	60%
Polyester + catalyst	90	75	45	30
Natural fibres (Sugar palm/Kenaf/Bamboo)	0	15	45	60
Fibreglass	5	5	5	5
Kevlar	5	5	5	5

Fig. 2 – Fabrication process of natural fibres hybrid fibreglass/Kevlar composite materials.

kenaf, and bamboo were cut by following the length of the mould. To avoid the specimen from sticking to the surface of the other mould, the steel mould was waxed and wiped. The stacking layer of materials in the composite began with Kevlar, followed by natural fibres (sugar palm/kenaf/bamboo), and lastly with fibreglass (CSM 225). To ensure that the materials were fully coated with resin, the resin was poured into the mould alternately with the materials. To avoid voids from forming, the surfaces of the matrix with surplus resin were rolled, forcing air and bubbles away from the specimens. Fig. 2 shows the fabrication process of natural fibres hybrid fibreglass/Kevlar composite materials.

2.3. *Tensile test*

The tensile test was performed to determine the force required to break a composite or plastic specimen and the extent to which the specimen stretches or elongates to that breaking point. The fabricated samples were cut according to the standard tensile test which was ASTM D3039. Five replicates from different natural fibres (sugar palm/kenaf/bamboo) hybrid fibreglass/Kevlar composites in each weight percentage were tested and the mean values were taken. The tests were performed in an INSTRON universal testing machine. After tensile tests, fragments of the break specimens were collected and analysed by Scanning Electron Microscopic (SEM).

2.4. *Impact test*

The Charpy impact was performed to determine the amount of energy absorbed by a material during fracture. The fabrication samples were cut according to the Charpy impact test and tensile test (ASTM D6110-10) standards. Five replicates from different natural fibres (sugar palm/kenaf/bamboo) hybrid fibreglass/Kevlar composites in each weight percentage were tested and the mean values were taken. The tests were performed in an INSTRON instrumented pendulum. After impact tests, fragments of the ruptured specimens were collected and analysed by Scanning Electron Microscopic (SEM).

2.5. *Water absorption test*

Water absorption testing was performed to study the percentage of water absorbed by the composite materials (Paladugu et al., 2021). The fabricated samples were cut according to the standard water absorption test ASTM D570-98. Five replicates from different natural fibres (sugar palm/kenaf/bamboo) hybrid fibreglass/Kevlar composites in each weight percentage were weighed and the mean values were taken. Firstly, the mass of samples was determined using a digital weighing balance before they were immersed in distilled water at room temperature. The weight of the samples was taken every 24 h until day 15. Fig. 3 below shows how the

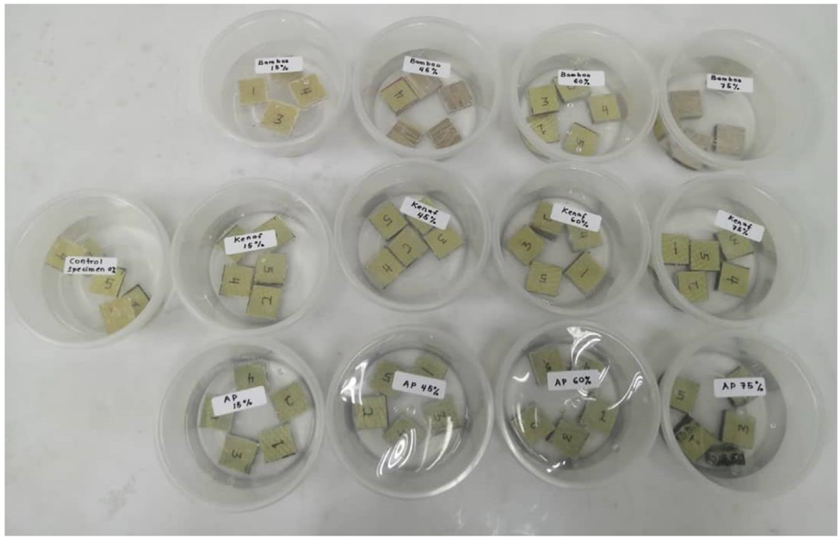

Fig. 3 – The immersion of samples in distilled water.

water absorption test was performed on the samples. The samples were then weighed to determine the weight gain before and after the test. Tissue paper was used to get rid of any surface water from the samples before weighing the mass. The following formula was used to calculate the percentage of water absorption:

$$\text{Water absorption }(\%) : \frac{Wt - Wo}{Wo} \times 100$$

Where,

Wo = mass of the sample at the beginning.

Wt = mass of the sample at different times.

3. Results and discussions

3.1. *Tensile test*

Because of their improved properties, natural fibre hybrid composites are increasingly being used in a variety of fields. This study on the hybridisation effect of natural fibres (sugar palm/bamboo/kenaf) hybrid with fibreglass/Kevlar as reinforcement merits researchers' attention due to their advanced mechanical properties. The tensile test result of natural fibres (sugar palm/bamboo/kenaf) hybrid with fibreglass/Kevlar reinforced composite is depicted in Fig. 4.

Three natural fibres were tested for mechanical properties in this tensile test. This natural fibre hybrid with fibreglass/Kevlar composites is tested in a universal testing machine until the sample breaks and the ultimate tensile strength is reached [31]. Fig. 4 (a) shows the result of the tensile strength (MPa) and tensile modulus (GPa) of sugar palm fibre hybrid fibreglass/Kevlar composite materials. The results indicated that the tensile strength and tensile modulus of 15% of weight content sugar palm fibres hybrid fibreglass/Kevlar composite are 58.23 MPa and 3.53 GPa, respectively. The 15% weight content of sugar palm showed the highest tensile strength and modulus amongst other weight content percentages. Meanwhile, the lowest tensile strength and modulus represent 45% of the weight content of sugar palm fibres, which were 45.74 MPa and 2.66 GPa, respectively. Sugar palm fibres are available in the form of fibre bundles. Another researcher stated that due to the non-homogeneous load distribution in fibre bundles, fibres were not loaded uniformly, and some individual fibres were not loaded at all. Moreover, sugar palm fibres have different orientations, which means that the orientation of the fibres is not consistent in only one direction. As a result, the sugar palm fibres were unable to successfully support the stress transferred from the polyester matrix, resulting in the failure of sugar palm fibre composites at lower loads [32]. The manufacturing defects in the fabrication process also influence the physical and mechanical properties of composites. A similar trend has shown that increasing the fibre loading is necessary to achieve maximum strength in the hybrid composite. Previous research found that the properties of hybrid composites were primarily determined by fibre content, length, orientation, arrangement, intermingling extent, and matrix adhesion. The addition of synthetic materials into the natural fibres revealed an increment in the tensile strength. The control sample has the highest tensile strength and modulus because of the glass fibre-reinforced composite, indicating a better adhesion between the fibreglass/Kevlar and polyester matrix. It is worth noting, however, that the incorporation of glass fibre into the sugar palm fibre composites has made the composite ductile [32]. Apart from that, a counter from other researchers stated that a result from previous research recorded the addition of sugar palm fibre to form a hybrid roselle/sugar palm composite caused a decrease in their tensile strength and modulus [33]. This could be due to poor adhesion, high void, fibre pullouts, incompatibility, or agglomeration, all of which could result in poor load transfer between the fibre and the matrix [33].

From Fig. 4 (b), the result of tensile strength and modulus of bamboo fibres hybrid fibreglass/Kevlar composite materials presented an increasing trend of the tensile strength and modulus. The 15% weight content decreased after the control sample because the control sample has higher tensile

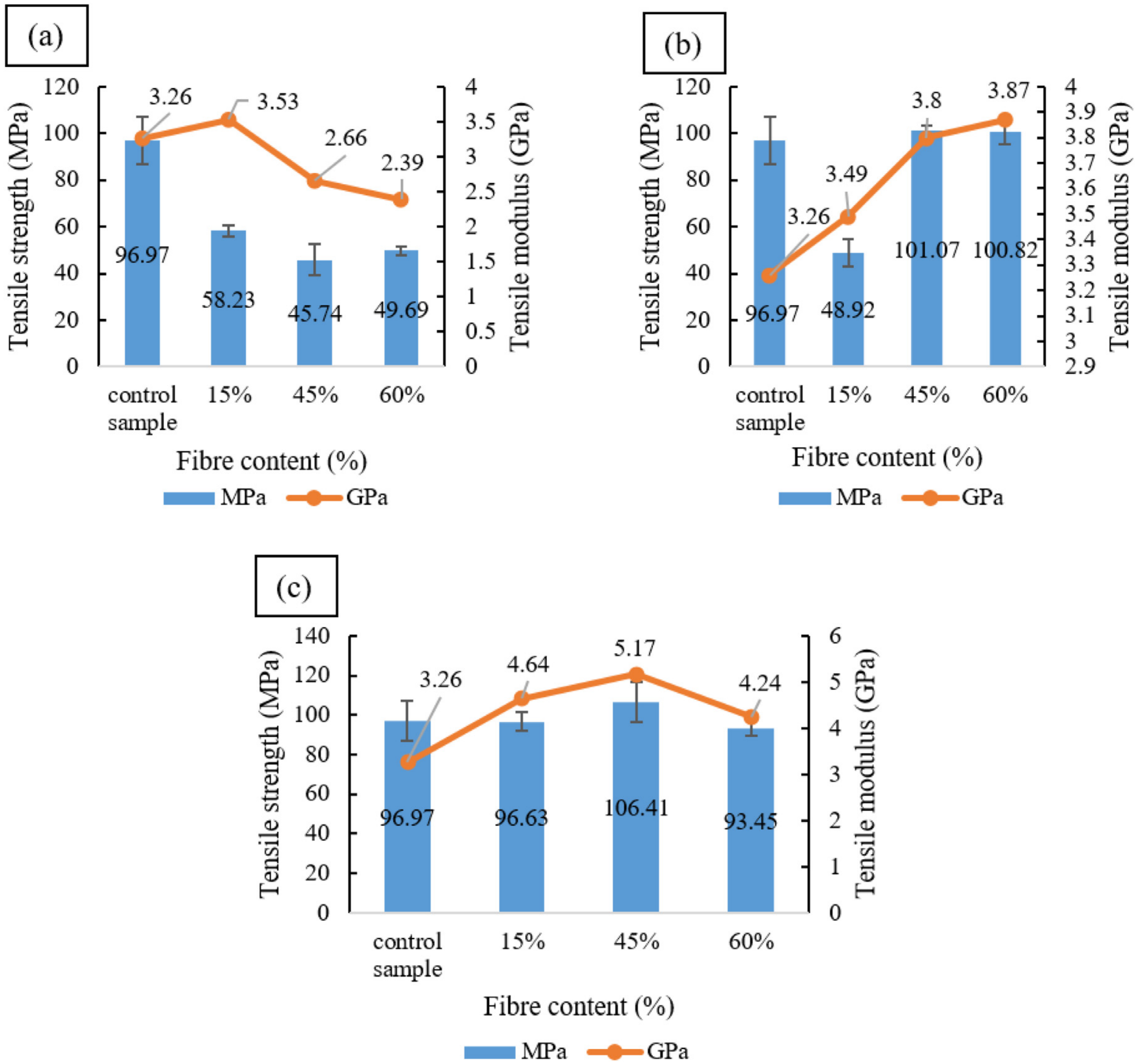

Fig. 4 – Tensile strength (MPa) and tensile modulus (GPa) of (a) sugar palm fibre, (b) bamboo, and (c) kenaf fibre hybrid fibreglass/Kevlar composite materials.

strength and modulus due to the glass fibre-reinforced composite, indicating a better adhesion between the fibreglass/Kevlar and polyester matrix, however, the 15% of weight content was insufficient to produce an effective reinforcement with a low percentage of fibre in the polyester matrix due to brittle fracture [34]. The 45% of weight content showed the maximum values of tensile strength and modulus which was 101.07 MPa and 3.8 GPa, respectively. The 60% of weight content bamboo fibres hybrid fibreglass/Kevlar composite materials demonstrated decrement in tensile strength after 45%, which was 100.82 MPa. According to another researcher, in their study on the characterisation of bamboo-fibreglass reinforced polymer matrix hybrid composite, the mechanical properties of the bamboo-fibreglass reinforced polypropylene hybrid systems depended on fibre weight ratios, fibre length, and adhesion characteristics between the fibres and the matrix [35]. The mould press method was used to determine the results with different bamboo fibres of 3 and 6 mm, and 10–40% of bamboo fibres were loaded with and without maleated polypropylene (MAPP). They observed when the bamboo fibre content was increased from 10 to 30%, the average tensile strength only improved slightly [35].

Fig. 4(c) depicts the result of tensile strength and modulus of kenaf fibre hybrid fibreglass/Kevlar composite materials. The highest tensile strength and modulus are shown in the sample of 45% kenaf fibre. The trend revealed an increment in tensile strength and modulus and decrements of both in 60% of weight-content fibre. The tensile strength values were 96.63, 106.41, and 93.45 MPa in samples 15, 45, and 60% of fibre weight content. Another study found that increasing the kenaf content in the weight of Kevlar/kenaf fibre in samples 26/74 wt% and above reduced the tensile properties of the hybrid composites. An increase of 10 to 20 wt% in the kenaf sample reduced hybrid composite tensile strength. A similar trend was observed in the tensile modulus [24]. This could be attributed to the presence of voids, as both tensile strength and modulus decreased as void content increased. Based on other studies, at low levels of fibre loading, the matrix was not

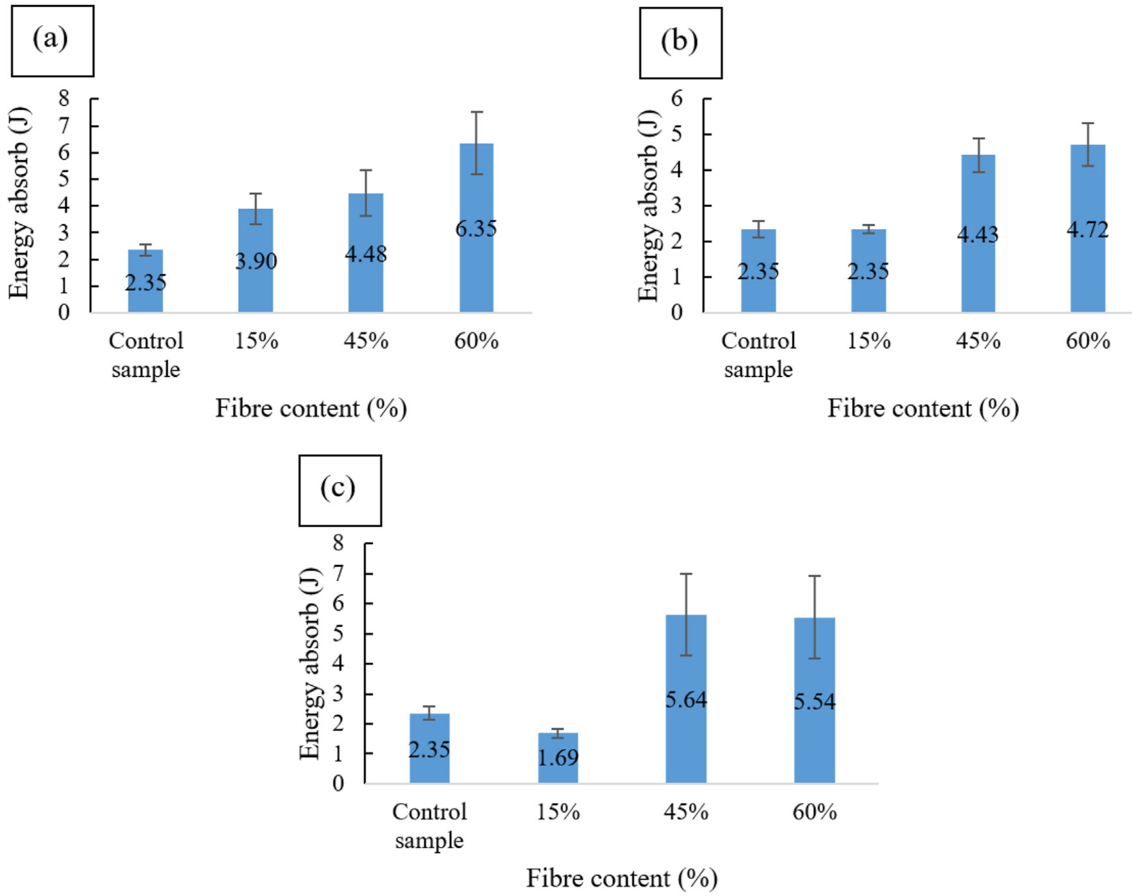

Fig. 5 – Energy absorption of (a) sugar palm fibre, (b) bamboo, and (c) kenaf fibre hybrid fibreglass/Kevlar composite materials.

reinforced by enough fibres, causing the bond between the matrix and fibre to break. The stress was more evenly distributed and the composite strength increased at intermediate loading levels (36 vol%). However, with further addition (i.e., to 62 vol%), the process became difficult with poor results in properties due to insufficient matrix resin wetting of the fibres [36].

3.2. *Charpy impact test*

Fig. 5 (a) shows the energy absorption of sugar palm fibre hybrid fibreglass/Kevlar composite materials. The highest result of energy absorption of sugar palm fibre is shown in the 60% of fibre content sample sugar palm. The result revealed a maximum of 6.35 J of energy absorbed, while the lowest energy was absorbed by the 15% sugar palm fibre sample, which was 3.90 J. Composite materials' impact properties were found to be directly related to their overall toughness, which was heavily influenced by interfacial bond strength, matrix properties, and fibre properties. Another researcher also found that the impact strength of hybrid composites increased as the fibre weight fraction increased. As this fraction increased, more energy must be expended to break the coupling between the interlaced fibres. Furthermore, the superior damage tolerance capability and efficient crack-resisting characteristics of fibreglass over sugar palm fibres had a significant impact on this result. Furthermore, as the weight of the glass/sugar palm fibres in the hybrid composites increased, additional impact absorption energy occurred between the fibres, increasing the impact resistance of the hybrid composites. Moreover, when the hybrid composites were impacted, the glass fibres were able to withstand the high-impact load while also absorbing a significant amount of impact energy via fibre delamination. As a result, the energy required to start and propagate the crack grew. Fibres play a crucial role in regulating the impact resistance in fibre-reinforced composites because they interact with the cracks formed in the matrix and act as a stress-transferring medium. A good interfacial region is created by the high bonding quality of the glass fibre and matrix. This condition improves the composite system's ability to absorb energy during fracture propagation and increases the impact resistance of hybrid composites [32,37].

Fig. 5 (b) illustrates the energy absorption of kenaf fibre hybrid fibreglass/Kevlar composite materials. The highest energy absorbed in kenaf fibres was in the 60% fibre. It possessed 4.72 J of the energy absorbed. The lowest of kenaf fibre hybrid composite materials depicted in the 15% of fibre content sample was 2.35 J. According to a similar achievement in other research, the level of maximum energy absorbed attained by 60% kenaf fibre content was the highest value under the same energy level. It might be attributed to an increase in composite stiffness caused by increased fibre

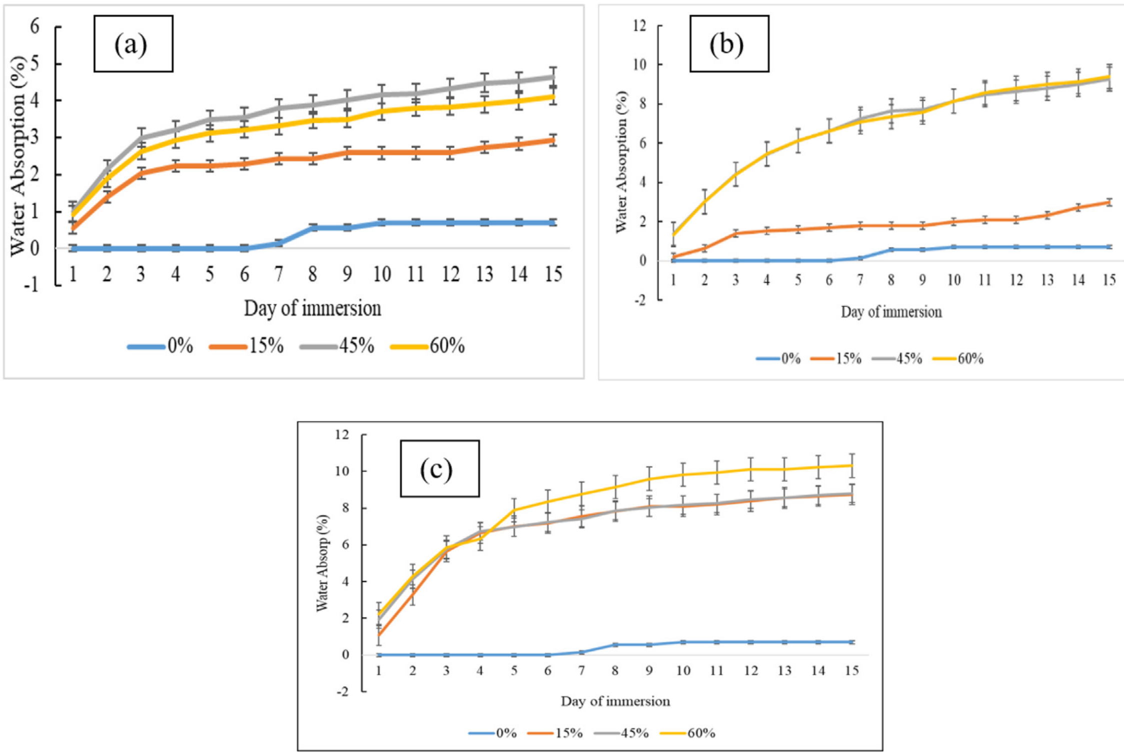

Fig. 6 – Water absorption properties of (a) sugar palm, (b) kenaf, and (c) bamboo fibre-reinforced hybrid fibreglass/Kevlar composite materials.

content in reinforced thermosetting plastics. It was completely obvious that the composite sample with 60% kenaf fibre content had maximum impact strength values than the other samples. In general, the impact energy is strongly influenced by the percentage of fibre content. Furthermore, low interfacial shear stress between natural fibres and polymer resin may contribute to composite strength increase. In other words, the incorporation of lignocellulosic fibres makes the propagation of an initial crack longitudinally through the interface following the specimen length direction more difficult [38].

Fig. 5 (c) depicts the result of energy absorption of bamboo fibre hybrid fibreglass/Kevlar composite materials. The highest result was shown in the 45% of the fibre sample and the lowest energy absorbed was shown in the 15% of the bamboo fibre sample. The highest and lowest results were 5.64 J and 1.69 J, respectively. The 15% decrease in bamboo fibre from the 0% (control sample) sample is insufficient to produce an effective reinforcement with a low percentage of fibre in the polyester matrix due to brittle fracture. Another study [34] stated that by visual analysis, a brittle fracture tendency in specimens with 0% and 10 vol% was observed, which was confirmed by the tested impact energy values. It showed a higher increase of more than 6 times from 10 to 20 vol% mallow fibres. It was perceived that the brittle fracture mechanism by the presence of “river marks”, both in the specimen with 100% epoxy as well as the composite with 10 vol% of fibre was present. These showed that there was no effective reinforcement at a low percentage of fibre. It should be noticed that, as in other works [34], an increase in average energy values with the fibre volume fraction used in the composite occurred. The 60% of fibre content exhibited decrement after 45% of bamboo fibre content due to more presence of natural fibre and more defects occurred in the specimen. A similar outcome stated that the mechanical properties of the bamboo-fibreglass reinforced polymer matrix hybrid composite depend on fibre weight ratios and length, as well as adhesion characteristics between the fibres and the matrix. Numerous microfibril loadings of bamboo were prepared. The impact strength of the composites was found to increase with the loading of bamboo microfibrils, reached an optimum, and then decreased with further loading of bamboo microfibrils [35].

3.3. *Water absorption test*

The water absorption percentage increased with immersion time and became stable after reaching saturation, and it was also influenced by the weight content percentage of the composite materials. The components of natural fibres consist of cellulose, hemicellulose, lignin, pectin, waxes, and water-soluble substances [39,40]. It is well known that natural fibre is hydrophilic because of the presence of the hydroxyl group. Each of the natural fibres has different components. Among the factors to reduce water absorption in composite materials are the chemical and physical treatments of fibres. Hybridisation between a natural fibre and a synthetic fibre in a single matrix can also improve the physical and mechanical properties [37,41–44]. Fig. 6 shows the water absorption percentage or weight gain in the natural fibre-reinforced (sugar palm/kenaf/bamboo) hybrid fibreglass/Kevlar composite materials with different weight content percentages which were 0 (control sample), 15, 45, and 60 wt%.

The percentages of water absorption for all of the samples are illustrated in Fig. 6. The rate of water absorption varied and depended on the duration of immersions. This is due to the different weight content percentages of natural fibres. The high fibre content in the samples allowed more water penetration into the interface via micro-cracks caused by the swelling of fibres and the increased water absorption until day 15. The water uptake was faster in the beginning and became slower when the immersion time was increased [45]. The 0% (control sample) fibre content sample showed the lowest weight gain percentage or water absorption since none of the natural fibres was in the sample. The 0% (control sample) fibre content sample reached the saturation point on day 15 which was at 0.70% weight gain.

As observed in Fig. 6 (a), (b) and (c), many factors are linked to the variations in water absorption such as the type of fibre, the composition of polymer and fibre, and layering arrangement [45]. From Fig. 6 (a), sugar palm fibres showed the lowest amount of water absorbed on day 15 for 15% fibre content which was at 2.94%. The percentage of fibre content in the sample also influenced the water absorption or weight gain percentage. This sample had the lowest fibre content, so the weight gain was also the lowest among the other fibre content percentages. From the previous research [9], it was observed that the sugar palm fibres were used in the composite to reduce water uptake as it has good water resistance. It was stated that since it can reduce the water uptake of composite materials, the combination of sugar palm fibres and other natural fibre composites became one of the factors behind the decline in the percentage of water absorption. Because of its high water resistance, sugar palm fibres are used in composites to reduce water uptake. Also, the combination of sugar palm fibre with roselle fibre resulted in a decrease in water absorption for all hybrid composite compositions. Furthermore, sugar palm fibre is well known for its seawater resistance. Because the fibre is resistant to seawater, it is commonly used in shipping ropes [46]. Hence, in this research, the 60% sugar palm fibre content showed decreased weight gain after 45% of fibre content due to the presence of the optimum natural fibres in the composite materials that can reduce water absorption. The 60% of fibre content sugar palm indicated 4.12% water absorption or weight gain percentage among other natural fibres on day 15. From this result, the presence of natural fibres in the composite and poor impregnated fibre with resin can also result in more water absorption in the composites. A similar case which reported an increase in moisture absorption content was found on other matrices using sugar palm fibre as the reinforcement or filler. The increase of sugar palm fibre incorporation increased the moisture intake of the hybrid composite by up to 9% [47]. Another study has proven that water molecules first enter the free space of micro-voids formed by cavities and cracks in the matrix during water immersion; at the same time, water molecules can rapidly penetrate and diffuse along the interface due to capillarity, increasing the weight of the sample [48].

The kenaf fibres depicted the lowest water weight gain percentage in 15% of fibre content in the composite which was 2.97%, as shown in Fig. 6 (b). The presence of less natural fibre and the good bonding between fibre-matrix affected the water uptake in the composites. The behaviour of the 45% fibre content samples after the water immersion for 15 days was examined. From the process of weight gain due to moisture uptake, it was observed that the samples had a sharp linear increase in their moisture absorption and reached a 9.26% weight gain percentage. The weight gain percentage for 60% fibre content was 9.39% of water absorption on day 15. The poor wettability of resin due to more presence of natural fibres in the sample also affected the percentage of water absorption or weight gain of composites. Previous research stated that the high fibre content in the samples allowed more water penetration into the interface via micro-cracks caused by the swelling of fibres, resulting in composite failure [49]. The fibreglass in this research also played a vital role in reducing water absorption [50]. In other research [40], the water absorption behaviour of kenaf fibre-reinforced unsaturated polyester composites was discovered to follow a Fickian's behaviour, where equilibrium was reached at a specific immersion time. They discovered that kenaf fibre-reinforced composite had a different magnitude of absorption characteristics in different solutions and that the moisture content increased with immersion time. However, the weight increase was not linear with the immersion time. The weight increased sharply at the start of the curve (up to 17 days of immersion), illustrating the rapid moisture penetration into the composite materials. This was true for all solutions considered in their research. They stated that this phenomenon was caused by water penetrability and capillary action, with water penetrating the interface through voids caused by swelling of the kenaf fibres [40].

Fig. 6 (c) shows the bamboo fibres obtained the lowest water absorption percentage in the 15% fibre content sample which was at 8.74% on day 15. The 45 and 60% fibre content samples showed that the weight gain percentage increased linearly, which were 8.79 and 10.31%, respectively on day 15. The treated natural fibre in this research had given better results in reducing water absorption by the composite. Alkali treatment of bamboo fibres and silane treatment of mercerised bamboo fibres resulted in greater hydrophobicity and less water absorption by the composite; lower initial rate of water absorption and less water absorption at saturation, according to various studies [50]. This is due to increased wettability and adhesion. Among the possible causes of this difference, the extraction of hemicellulose by alkali treatment stood out because hemicellulose was thought to be primarily responsible for water uptake due to its greater accessibility than the crystalline regions of the cellulose [50]. Another report stated that water absorption was reduced by alkali treatment from 51 to 35%. Silane treatment resulted in even more reduction. Water absorption ranged from 19 to 44%, with bamboo composite with silane treatment absorbing the least. The improved moisture resistance caused by the coupling agent can be explained by improved fibre-matrix adhesion. Alkali treatment activated inactive hydroxyl groups, resulting in improved silane deposition and the possibility of a strong chemical interaction between the fibre and matrix [42]. A similar trend was reported by Widiastuti et al. [30] that at the same temperature, the bamboo-epoxy composite absorbed more water than the pure epoxy specimen. The water absorption of bamboo-epoxy composites varied with time for different immersion temperatures. When considering service application, the effect of temperature on the water absorption process must be considered. Water sorption increased with immersion time at all immersion temperatures.

3.4. *Surface morphology*

Morphological surfaces analysis determined by SEM was carried out to comprehend further the relationship between manufacturing defects and mechanical properties of natural fibre hybrid fibreglass/Kevlar composite materials. For the tensile test, the lowest tensile strength amongst three natural fibres was depicted in the sample 45% of fibre content sugar palm fibres of 45.74 MPa. This might be due to poor interfacial adhesion between fibre-matrix. Fig. 7 below shows the manufacturing defects that occur in the sample 45% sugar palm fibre hybrid fibreglass/Kevlar composite materials. The poor interfacial adhesion between the fibre and matrix occurred in the region where the resin did not sufficiently wet the fibres. There was a distinct gap observed between the fibre and the matrix [38]. The other defects were also clearly seen in the sample such as voids, misaligned fibres, and fibre pull-out. The highest tensile strength amongst the three natural fibres is illustrated in the sample of 45% kenaf fibres hybrid fibreglass/Kevlar composite materials. In Fig. 8, the least defects were observed in the sample of 45% kenaf fibres hybrid fibreglass/Kevlar composite materials. Fig. 8 shows obvious voids and fibre pull-out. As previously stated, voids are typically defined as air bubbles stuck in the matrix during composite fabrication, but voids can be caused by a variety of factors. Voids can also form as a result of impurities in commercial epoxy resins used for fibre-reinforced composites, which can have a significant impact on the resin's cure behaviour [38]. Thus, the defects that occurred in the composite sample to some extent can impact the performance of mechanical properties of hybrid composite materials.

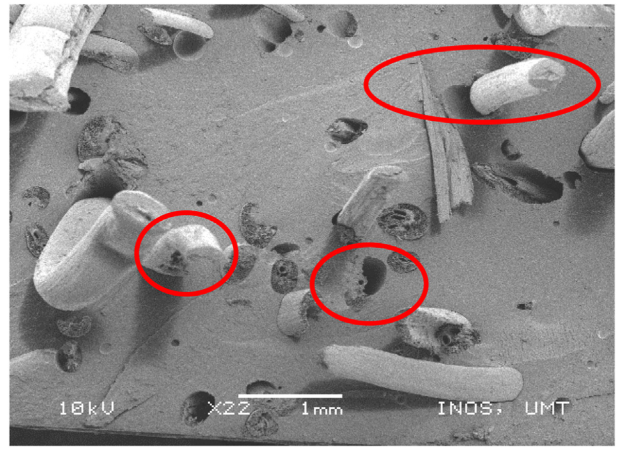

Fig. 8 – Voids and fibre pull-out observed in the sample 45% of kenaf fibres hybrid fibreglass/Kevlar composite materials.

Generally, fibre content percentage strongly influenced the impact energy of the composites. Furthermore, the low interfacial shear stress between natural fibre and polymer resin may lead to a composite strength increase. In certain words, the utilisation of lignocellulose fibres presented challenges to the longitudinal spreading of an initial crack through the interface following [38]. The Charpy impact sample also carried out the SEM morphology test to observe the defects that occurred in the sample. The lowest energy absorbed was observed in the sample 15% of bamboo fibres hybrid fibreglass/Kevlar composite materials. Fig. 9 shows defects detected in the sample. The defects in the sample were obviously seen such as voids, fibre pull-out, and weak interfacial adhesion between fibre-matrix. The impact properties of the composite were reduced due to more manufacturing defects in the composites. Fig. 10 shows the SEM in the highest energy absorption of 60% of sugar palm fibre hybrid fibreglass/Kevlar

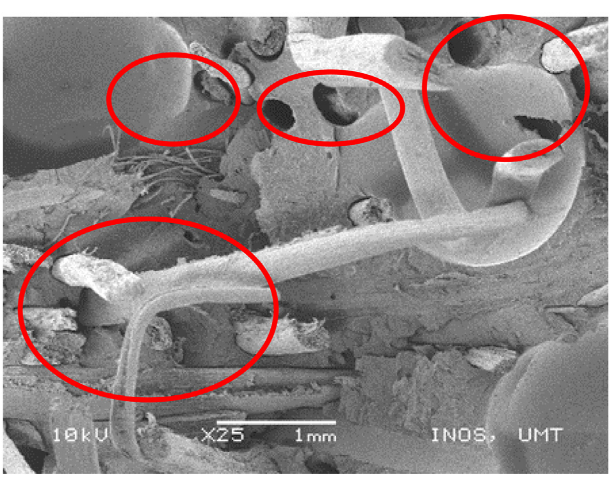

Fig. 7 – Poor interfacial adhesion between fibre-matrix, voids, fibre pull-out, and misalignment of fibre observed in the sample 45% of sugar palm fibre hybrid fibreglass/Kevlar composites.

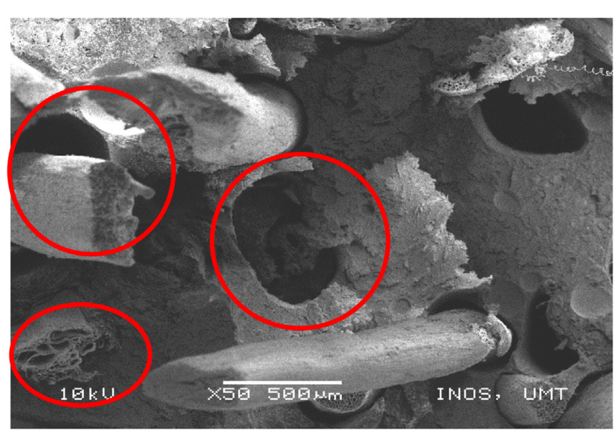

Fig. 9 – Voids, fibre pull-out, and poor interfacial adhesion of fibre-matrix occurred in the sample 15% of bamboo fibres hybrid fibreglass/Kevlar composite materials.

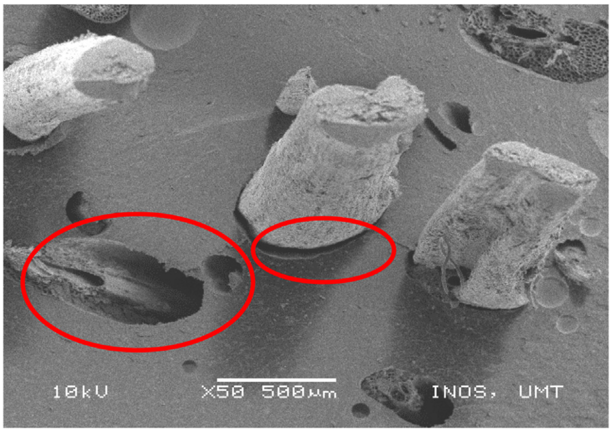

Fig. 10 – Voids and poor interfacial adhesion between the fibre-matrix of 60% sugar palm hybrid fibreglass/Kevlar composite materials.

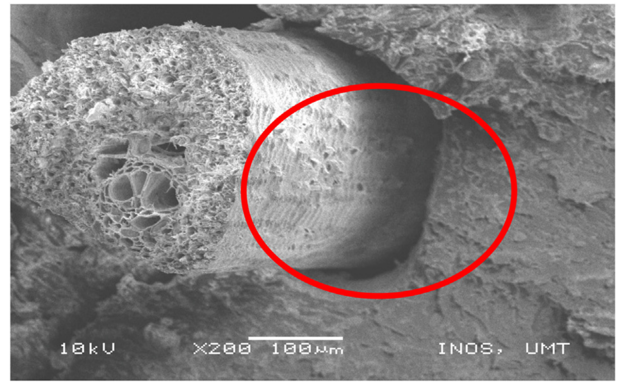

Fig. 12 – The debonding between fibre and matrix in specimen of sugar palm fibres hybrid fibreglass/Kevlar composite materials after immersion.

composite materials. The least occurred defects influenced the highest energy absorption in the sugar palm specimen.

The example cross-section surface study of the laminated sugar palm fibre hybrid with fibreglass/Kevlar composite after the water sorption test is shown in Figs. 11 and 12. The cross-sectional observation of the specimens was focused on the interfacial of the natural fibres and the matrix. As shown in this Fig. 11, the SEM photograph of the cross-section surface of the dry material indicates good adhesion between the natural fibre hybrid composite and the polyester matrix. However, large spaces were found in the specimens immersed in the water. It is observed from Fig. 12 for immersion at room temperature, that a debonding developed between the fibre and matrix in the water-immersed specimens. The water molecules penetrated the natural fibre laminate composite and affects the interfacial adhesion between the fibre and the matrix. The hydrophilic nature of natural fibre caused the laminate composite to absorb more water. The sugar palm fibre hybrid with fibreglass/Kevlar composite in Fig. 12 shows that the water uptake caused swelling of sugar palm fibres. The swelling created micro-cracks in the polymer matrix and eventually led to debonding between the fibre and the matrix. The sorption-induced swelling stress may also lead to composite failure, delamination and loss of structural integrity, especially due to varying liquid content within the material [30].

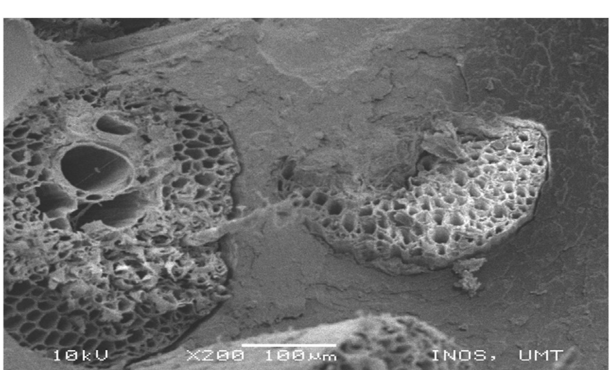

Fig. 11 – Dry specimen of sugar palm fibres hybrid fibreglass/Kevlar composite materials.

4. Conclusions

This study was conducted to discover the tensile, impact, and water absorption properties that identify the tensile strength, tensile modulus, energy absorption characteristics, and water uptake percentage of different natural fibres, which are sugar palm/kenaf/bamboo fibres hybrid fibreglass/Kevlar reinforced with a polyester matrix. The tensile test amongst three natural fibres showed that the highest tensile strength and tensile modulus were depicted in the sample of 45% kenaf fibres hybrid fibreglass/Kevlar composite materials. It revealed 106.41 MPa of tensile strength and 5.17 GPa for tensile modulus. The highest impact properties, which is the determination of the highest energy absorption were shown in the 60% sugar palm fibre hybrid fibreglass/Kevlar composite sample amongst the three natural fibre composites, which was 6.35 J. The water absorption result showed the least weight gain in the sugar palm fibres hybrid fibreglass/Kevlar composite materials. It demonstrated the result of a 2.94% water absorption percentage. The least water absorption percentage showed the best water resistance for the material composites. Some of the factors that affect the performance of natural fibre hybrid composite materials were uneven dispersion of fibres in the specimen, causing the region that was poorly wetted with resin to experience fibre pull-out, and when the load is applied to the composite surface, composite failure will likely occur. The composite also experienced manufacturing defects due to weak interfacial adhesion, voids, misaligned fibres, and fibre pull-out that directly influenced the performance of tensile and impact properties. Furthermore, manufacturing defects in the composite must be taken seriously because they significantly affect the physical and mechanical properties of the composites. A good composite primarily consists of the fewest manufacturing defects. The highest manufacturing defects discovered in composites during fabrication significantly reduced tensile and impact behaviour results and indicated high water absorption results.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was funded by the Fundamental Research Grant Scheme (FRGS) FRGS/1/2020/TK0/UMT/02/4/Correlation of Manufacturing Defects, Interfacial Adhesion, Physical, and Mechanical Properties of Plant Fibre Reinforced Hybrid Composite Material towards Compatibility Behaviors/Vot. No 59624. The authors would like to acknowledge all researchers of Marine Materials Research Group, technicians, and support staff from Maritime Technology Lab, UMT, Bio-composite Lab, INTROP, Advanced Engineering Materials and Composites Research Centre, UPM and MSET Inflatable Composit Sdn. Bhd. for their countless support and services. The authors would like to express gratitude for the financial support received from the Universiti Teknologi Malaysia for the project "The impact of Malaysian bamboos' chemical and fibre characteristics on their pulp and paper properties", grant number PY/2022/02318— Q. J130000.3851.21H99. The research has been carried out under the programme, Research Excellence Consortium (JPT (BPKI) 1000/016/018/25 (57)), provided by the Ministry of Higher Education Malaysia (MOHE).

REFERENCES

[1] Nazim ARM, Ansari MNM, Atiqah A. Impact strength and morphological properties of Kenaf/glass fibre/polyester hybrid composite for attenuator application. Mater Today Proc 2019;29:119–22. https://doi.org/10.1016/j.matpr.2020.05.683.

[2] Azman MA, Asyraf MRM, Khalina A, Petrů M, Ruzaidi CM, Sapuan SM, et al. Natural fiber reinforced composite material for product design: a short review. Polymers 2021;13:1917. https://doi.org/10.3390/polym13121917.

[3] Norfarhana AS, Ilyas RA, Ngadi N. A review of nanocellulose adsorptive membrane as multifunctional wastewater treatment. Carbohydr Polym 2022;291:119563. https://doi.org/10.1016/j.carbpol.2022.119563.

[4] Norfarhana AS, Ilyas RA, Ngadi N, Sharma S, Sayed MM, Nordin AH. Natural fiber-reinforced thermoplastic enr/PVC composites as potential membrane technology in industrial wastewater treatment : a review. Polymers 2022;14:1–30. https://doi.org/10.3390/polym14122432.

[5] Sharma S, Sudhakara P, Omran AAB, Singh J, Ilyas RA. Recent trends and developments in conducting polymer nanocomposites for multifunctional applications. Polymers 2021;13:2898. https://doi.org/10.3390/polym13172898.

[6] Kadier A, Ilyas RA, Huzaifah MRM, Harihastuti N, Sapuan SM, Harussani MM, et al. Use of industrial wastes as sustainable nutrient sources for bacterial cellulose (BC) production : mechanism , advances , and future perspectives. Polymers 2021;13:1–51. https://doi.org/10.3390/polym13193365.

[7] Aiza Jaafar CN, Zainol I, Ishak NS, Ilyas RA, Sapuan SM. Effects of the liquid natural rubber (LNR) on mechanical properties and microstructure of epoxy/silica/kenaf hybrid composite for potential automotive applications. J Mater Res Technol 2021;12:1026–38. https://doi.org/10.1016/j.jmrt.2021.03.020.

[8] Nurazzi NM, Sabaruddin FA, Harussani MM, Kamarudin SH, Rayung M, Asyraf MRM, et al. Mechanical performance and applications of CNTs reinforced polymer composites—a review. Nanomaterials 2021;11:2186. https://doi.org/10.3390/nano11092186.

[9] Radzi AM, Sapuan SM, Jawaid M, Mansor MR. Water absorption, thickness swelling and thermal properties of roselle/sugar palm fibre reinforced thermoplastic polyurethane hybrid composites. J Mater Res Technol 2019. https://doi.org/10.1016/j.jmrt.2019.07.007.

[10] Ilyas RA, Sapuan SM, Harussani MM, Hakimi MYAY, Haziq MZM, Atikah MSN, et al. Polylactic acid (PLA) biocomposite: processing, additive manufacturing and advanced applications. Polymers 2021;13:1326. https://doi.org/10.3390/polym13081326.

[11] Diyana ZN, Jumaidin R, Selamat MZ, Ghazali I, Julmohammad N, Huda N, et al. Physical properties of thermoplastic starch derived from natural resources and its blends: a review. Polymers 2021;13:1–20. https://doi.org/10.3390/polym13091396.

[12] Ismail MF, Sultan MTH, Hamdan A, Shah AUM. A study on the low velocity impact response of hybrid Kenaf-Kevlar composite laminates through drop test rig technique. Bioresources 2018;13:3045–60. https://doi.org/10.15376/biores.13.2.3045-3060.

[13] Sabaruddin FA, Paridah MT, Sapuan SM, Ilyas RA, Lee SH, Abdan K, et al. The effects of unbleached and bleached nanocellulose on the thermal and flammability of polypropylene-reinforced kenaf core hybrid polymer bionanocomposites. Polymers 2020;13:116. https://doi.org/10.3390/polym13010116.

[14] Ravishankar B, Nayak SK, Kader MA. Hybrid composites for automotive applications – a review. J Reinforc Plast Compos 2019;38:835–45. https://doi.org/10.1177/0731684419849708.

[15] Fernando G. Hybrid composites a review. Acta Mater 2009;23:314–45.

[16] Nurazzi NM, Asyraf MRM, Khalina A, Abdullah N, Aisyah HA, Rafiqah SA, et al. A review on natural fiber reinforced polymer composite for bullet proof and ballistic applications. Polymers 2021;13:646. https://doi.org/10.3390/polym13040646.

[17] Nurazzi NM, Asyraf MRM, Fatimah Athiyah S, Shazleen SS, Rafiqah SA, Harussani MM, et al. A review on mechanical performance of hybrid natural fiber polymer composites for structural applications. Polymers 2021;13:2170. https://doi.org/10.3390/polym13132170.

[18] Senthilkumar K, Saba N, Rajini N, Chandrasekar M, Jawaid M, Siengchin S, et al. Mechanical properties evaluation of sisal fibre reinforced polymer composites : a review. Construct Build Mater 2018;174:713–29. https://doi.org/10.1016/j.conbuildmat.2018.04.143.

[19] Shukla N, Devnani GL. A review on mechanical properties of hybrid natural fiber polymer composites. Mater Today Proc 2021:1–4. https://doi.org/10.1016/j.matpr.2021.01.122.

[20] Maharana SM, Pradhan AK, Pandit MK. Moisture absorption behaviour of nanofiller reinforced jute-kevlar hybrid polymer composite. Mater Today Proc 2019;26:775–80. https://doi.org/10.1016/j.matpr.2020.01.025.

[21] Sathishkumar TP, Naveen J, Satheeshkumar S. Hybrid fiber reinforced polymer composites - a review. J Reinforc Plast

Compos 2014;33:454–71. https://doi.org/10.1177/0731684413516393.

[22] Venkateshwaran N, Elayaperumal A, Sathiya GK. Prediction of tensile properties of hybrid-natural fiber composites. Compos B Eng 2012;43:793–6. https://doi.org/10.1016/j.compositesb.2011.08.023.

[23] Atiqah A, Maleque MA, Jawaid M, Iqbal M. Development of kenaf-glass reinforced unsaturated polyester hybrid composite for structural applications. Compos B Eng 2014;56. https://doi.org/10.1016/j.compositesb.2013.08.019.

[24] Yahaya R, Sapuan SM, Jawaid M, Leman Z, Zainudin ES. Mechanical performance of woven kenaf-Kevlar hybrid composites. J Reinforc Plast Compos 2014;33. https://doi.org/10.1177/0731684414559864.

[25] Chandramohan D, Dhanashekar M, Sathish T, Kumar SD. Characterization of hybrid aloe vera/bamboo/palm/kevlar fibers for better mechanical properties. Mater Today Proc 2020;37:2223–7. https://doi.org/10.1016/j.matpr.2020.07.657.

[26] Yu Y, Liu R, Huang Y, Meng F, Yu W. Preparation, physical, mechanical, and interfacial morphological properties of engineered bamboo scrimber. Construct Build Mater 2017;157:1032–9. https://doi.org/10.1016/j.conbuildmat.2017.09.185.

[27] Asyraf MRM, Ishak MR, Syamsir A, Nurazzi NM, Sabaruddin FA, Shazleen SS, et al. Mechanical properties of oil palm fibre-reinforced polymer composites: a review. J Mater Res Technol 2022;17:33–65. https://doi.org/10.1016/j.jmrt.2021.12.122.

[28] Essabir H, Boujmal R, Ouadi M, Rodrigue D, Bouhfid R. Mechanics of Materials Mechanical and thermal properties of hybrid composites. Oil-palm fiber/clay reinforced high density polyethylene 2016;98:36–43. https://doi.org/10.1016/j.mechmat.2016.04.008.

[29] Shinoj S, Visvanathan R, Panigrahi S, Varadharaju N. Dynamic mechanical properties of oil palm fibre (OPF) -linear low density polyethylene (LLDPE) biocomposites and study of fibre e matrix interactions. Biosyst Eng 2015;109:99–107. https://doi.org/10.1016/j.biosystemseng.2011.02.006.

[30] Widiastuti I, Pratiwi YR, Cahyo DN. A study on water absorption and mechanical properties in epoxy-bamboo laminate composite with varying immersion temperatures. Open Eng 2020;10:814–9. https://doi.org/10.1515/eng-2020-0091.

[31] Zakikhani P, Zahari R, Sultan MTH, Majid DL. Morphological, mechanical, and physical properties of four bamboo species. Bioresources 2017;12:2479–95. https://doi.org/10.15376/biores.12.2.2479-2495.

[32] Sapuan SM, Lok HY, Ishak MR, Misri S. Mechanical properties of hybrid glass/sugar palm fibre reinforced unsaturated polyester composites. Chinese J Polym Sci (English 2013;31:1394–403. https://doi.org/10.1007/s10118-013-1342-4.

[33] Radzi AM, Sapuan SM, Jawaid M, Mansor MR. Mechanical performance of roselle/sugar palm fiber hybrid reinforced polyurethane composites. Bioresources 2018;13:6238–49. https://doi.org/10.15376/biores.13.3.6238-6249.

[34] Nascimento LFC, Monteiro SN, Louro LHL, Luz FS Da, Santos JL Dos, Braga FDO, et al. Charpy impact test of epoxy composites reinforced with untreated and mercerized mallow fibers. J Mater Res Technol 2018;7:520–7. https://doi.org/10.1016/j.jmrt.2018.03.008.

[35] Rassiah K, Megat Ahmad MH, Kem Sg, Besi M, Lumpur K. A review on mechanical properties of bamboo fiber reinforced polymer composite. Aust J Basic Appl Sci 2013;7:247–53.

[36] Öztürk S. Effect of fiber loading on the mechanical properties of kenaf and fiberfrax fiber-reinforced phenol-formaldehyde composites. J Compos Mater 2010;44:2265–88. https://doi.org/10.1177/0021998310364265.

[37] Mohd Nurazzi N, Khalina A, Sapuan SM, Ilyas RA. Mechanical properties of sugar palm yarn/woven glass fiber reinforced unsaturated polyester composites: effect of fiber loadings and alkaline treatment. Polimery/Polymers 2019;64. https://doi.org/10.14314/polimery.2019.10.3.

[38] Suriani MJ, Sapuan SM, Ruzaidi CM, Naveen J, Syukriyah H. Correlation of manufacturing defects and impact behaviors of kenaf fiber reinforced hybrid fiberglass/Kevlar polyester composite. 2021. p. 30. –5.

[39] Suriani MJ, Rapi HZ, Ilyas RA, Petrů M, Sapuan SM. Delamination and manufacturing defects in natural fiber-reinforced hybrid composite: a review. Polymers 2021;13:1323. https://doi.org/10.3390/polym13081323.

[40] Akil HM, Omar MF, Mazuki AAM, Safiee S, Ishak ZAM, Abu Bakar A. Kenaf fiber reinforced composites: a review. Mater Des 2011;32:4107–21. https://doi.org/10.1016/j.matdes.2011.04.008.

[41] Tezara C, Hadi AE, Siregar JP, Muhamad Z, Hamdan MHM, Oumer AN, et al. The effect of hybridisation on mechanical properties and water absorption behaviour of woven jute/ramie reinforced epoxy composites. Polymers 2021;13. https://doi.org/10.3390/polym13172964.

[42] Kushwaha PK, Kumar R. Studies on water absorption of bamboo-polyester composites: effect of silane treatment of mercerized bamboo. Polym Plast Technol Eng 2010;49:45–52. https://doi.org/10.1080/03602550903283026.

[43] Asim M, Jawaid M, Abdan K, Ishak MR. Effect of alkali and silane treatments on mechanical and fibre-matrix bond strength of kenaf and pineapple leaf fibres. J Bionic Eng 2016;13:426–35. https://doi.org/10.1016/S1672-6529(16)60315-3.

[44] Audibert C, Andreani AS, Lainé É, Grandidier JC. Mechanical characterization and damage mechanism of a new flax-Kevlar hybrid/epoxy composite. Compos Struct 2018;195:126–35. https://doi.org/10.1016/j.compstruct.2018.04.061.

[45] Hamdan MHM, Siregar JP, Cionita T, Jaafar J, Efriyohadi A, Junid R, et al. Water absorption behaviour on the mechanical properties of woven hybrid reinforced polyester composites. Int J Adv Manuf Technol 2019;104:1075–86. https://doi.org/10.1007/s00170-019-03976-9.

[46] Asyraf MRM, Syamsir A, Supian ABM, Usman F, Ilyas RA, Nurazzi NM, et al. Sugar palm fibre-reinforced polymer composites: influence of chemical treatments on its mechanical properties. Materials 2022;15. https://doi.org/10.3390/ma15113852.

[47] Bahrain SHK, Masdek NRN, Mahmud J, Mohammed MN, Sapuan SM, Ilyas RA, et al. Morphological, physical, and mechanical properties of sugar-palm (arenga pinnata (wurmb) merr.)-reinforced silicone rubber biocomposites. Materials 2022;15:4062. https://doi.org/10.3390/ma15124062.

[48] Gu H, Hongxia S. Delamination behaviour of glass/polyester composites after water absorption. Mater Des 2008;29:262–4. https://doi.org/10.1016/j.matdes.2006.11.010.

[49] Rashdi AAA, Salit MS, Abdan K, Megat MMH. Water absorption behaviour of kenaf reinforced unsaturated polyester composites and its influence on their mechanical properties. Pertanika J Sci Technol 2010;18:433–40.

[50] Gupta MK, Deep V. Effect of water absorption and stacking sequences on the properties of hybrid sisal/glass fibre reinforced polyester composite. Proc Inst Mech Eng Part L J Mater Des Appl 2019;233:2045–56. https://doi.org/10.1177/1464420718811867.