MECHANICAL PROPERTIES OF SHORT AND CONTINUOUS KENAF/PET FIBRE REINFORCED POLYOXYMETHYLENE COMPOSITE

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ABSTRACT

The challenges of improving the mechanical properties of natural fibre composites cannot be over emphasized due to fibre geometry, poor fiber distribution in the matrix, the hydrophilic nature of natural fibers and poor fibre–matrix interfacial adhesion. The primary objective of this research is to study the influence of fibre length on mechanical properties of kenaf/PET fibre reinforced POM and to study the effect of hybridization on mechanical properties of the composites. The composites were produced by compression molding and subsequently subjected to tensile, flexural and impact tests according to their respective ASTM standards. The tensile strength of short POM/kenaf/PET (80/10/10) hybrid composite dropped by approximately 33% from 61.8 MPa to 41.3 MPa compared to neat POM. However, the tensile strength of continuous POM/kenaf composites increased significantly by approximately 127% and 107% for 70/30 and 80/20 compositions compared to neat POM. The flexural moduli of short POM/kenaf/PET (70/15/15) hybrid composite and continuous POM/kenaf (70/30) composite improved by approximately 41% and 29%, respectively. The impact strength substantially increased by nearly 161% in continuous POM/kenaf/PET (70/15/15) hybrid composite and 30% in POM/kenaf (80/20) composite. The results show that tensile, flexural and impact properties of the continuous POM/kenaf composites are superior to the short fiber composites, and the influence of hybridization, made a positive impact by enhancing the flexural and impact properties of the composites.

Keywords: Natural fibres; mechanical properties; hybrid composites; morphology

1. INTRODUCTION

Natural fibres form an interesting substitute for the most commonly used fibres in the composite industry because of low cost, low specific weight and ease of fabrication. Natural fibres are also referred to as natural composites since they consist of microfibril in lignin and hemicellulose matrix [1, 2]. When these fibres are used in a matrix, they serve as the main load carrying member in the composite while the matrix helps to bind the fibres together, transfer load to the fibers and protect the fibres from environmental attack. The matrix also has an influence in the composite transverse modulus, shear strength and compressive strength. The most widely used matrix for natural fibre composites are thermoplastics and thermosets. The collective attributes of natural fibre and thermoplastic matrix can produce a composite with high strength to weight ratio due to matrix flexibility. One of the factors that limit the large scale production of natural fibres is its low strength in composites compared to glass fibre, which is often a result of poor fiber-matrix interfacial tension. The wettability of the natural fibres with polymer matrix is less compared to glass fibre. Another major factor limiting the large scale production of natural fibers is water absorption [3, 4]. The water absorption caused the composite to deform by swelling thereby creating voids which in turn reduced the strength of the composite. Chemical treatment of the natural fibers such as mercerization leads to fibrillation, which results in the breaking down of composite fiber bundles into smaller ones. This reduces the fibre diameter, thus increasing the aspect ratio leading to rough surface for better mechanical interlocking with the matrix [1, 5]. For the purpose of this research, kenaf fiber was selected due to its availability and good mechanical properties in thermoplastic matrix. PET fibre was selected due to its high tensile strength, high elastic modulus and retains its mechanical properties during recycling process [6].

The low performance of natural fibre composites in high strength applications has attracted the attention of researchers to adopt new strategies for improving their mechanical properties. The first approach was surface treatment of natural fibres for better interface bonding with the matrix, secondly is fibre distribution and lastly hybridization with synthetic fibres. Surface treatments of natural fibres require the use of aliphatic groups which consists of functional groups that can react with the matrix in an attempt to improve its surface energy and make the fibre moisture resistant [7 - 9].

The tensile and flexural property of kenaf fibre reinforced composites largely depends on the fibre content, orientation and manufacturing process used. A research conducted by Ochi [10] revealed that increasing the fibre content up to 70%, marginally increased the tensile and flexural strength of kenaf fibre reinforced polylactic acid (PLA) composite to 223 MPa and 254 MPa, respectively. The results confirmed that kenaf fibre exhibit higher strength in tension and flexure compared to other natural fibres when reinforced with PLA [11]. The mechanical properties and fractured behaviour of short PET fibre waste-polyethylene (WPE) composite was studied [12]. Short PET fibre reinforced WPE obtained from waste carry bags and neat HDPE were prepared in a Brabender by melt mixing method under optimum processing condition. Maleic anhydride (MAH) grafting was also done on the WPE matrix and separate composite samples of WPE-PET were produced. The results from mechanical testing revealed that the tensile strength of the composite improved significantly with increasing fibre loading in the matrix and upon grafting the WPE matrix with MAH. The flexural strength of the composite improved significantly by approximately 59% from 25.4 to 40.5 MPa. Similar results were reported by other researchers were the addition of reinforcing materials, significantly improved the mechanical properties of composites [13].

The mechanical properties of natural fibre composites strongly depend on fibre direction, interfacial bonding between the hydrophilic natual fibre, and the hydrophobic polymer and fibre distribution. From a recent study conducted on the short fiber mat, low tensile and flexural strength were obtained due to the random orientation of the fibres in the matrix [2]. The use of twisted short fibres to produce yarn offers a viable alternative in improving the composite mechanical properties. The yarn is a long continuous assembly of twisted short fibres that are commonly used in textile, knitting, weaving, braiding and sewing. In this research, short and continuous kenaf fibres were distinctly reinforced in POM matrix to study the changes in mechanical properties due to increase in fibre loading and hybridization with PET fibre.

The primary objective of this study is to investigate the variation in mechanical properties exhibited by short and continuous kenaf fibre composites and also to explore the influence of hybridization on mechanical properties of the composites. Natural fibre composites produced by hybridization with synthetic fibres, have the tendency of exhibiting high mechanical properties and low water absorption rate. Such composites can be used for outdoor application in the automotive industry and in civil engineering constructions. However, it is important to note that surface treatment of kenaf fibre was not carried out throughout the production process, and this is to avoid the degradation of lignin and cellulose content of kenaf fibre that is usually experienced during chemical treatment. The weight percentage composition of short and continuous POM/kenaf composite was maintained at 80/20 and 70/30, respectively. Likewise, the weight percentage of short and continuous POM/kenaf/PET hybrid composite was maintained at 80/10/10 and 70/15/15.

Fig. 1: A three dimensional randomly oriented short kenaf fibre mat.

2. MATERIALS AND METHODS

2.1 Materials

A three dimensional randomly oriented short kenaf fibre mat with a fibre diameter of approximately

0.1mm and an average fibre length of nearly 7mm was used for the production of samples as shown in Fig. 1. Similarly, a continuous kenaf yarn with a diameter of approximately 1mm and PET yarn with a diameter of nearly 0.3 mm were also used as reinforcements. The kenaf yarn has a density of approximately 1.32 g/cm^3 while the PET yarn has a density of nearly 1.38 g/cm^3. The percentage elongation of the kenaf and PET yarn stands at 1.6% and 24.8%, respectively. The polymer matrix used was Acetal copolymer (POM) with melt flow index (MFI) of 9 g/10 min and with a tensile strength of approximately 63 MPa. Figs. 2 and 3 shows the pictorial view of the continuous kenaf, and PET yarn used in this study, and all production materials were supplied by Innovative Pultrusion Sdn. Bhd, Malaysia.

2.2 Equipment

A compression moulding machine manufactured by Carver Inc., USA with a temperature capacity of 400^{o}C was used alongside a domestic fan to aid the cooling process. During mechanical testing, tensile and flexural tests were carried out using a universal material testing machine according to ASTM D638 and D790, respectively. A universal impact testing machine was used for notched Charpy impact test according to ASTM D6110. An average of 10 samples was used to compute the final results of the investigation as specified in the ASTM guideline for testing polymer composites. The void content of the composites was determined by using a digital densimeter containing distilled water.

Fig. 2: A continuous twisted kenaf yarn

Fig. 3: A continuous PET yarn

2.3 Production of short and continuous POM/kenaf composites

The process started with the production of thin layers of neat POM by compression moulding using a pressure and processing temperature of 130 MPa and 190^{o}C, respectively. The thin layers were subsequently cooled under pressure to approximately 80^{o}C before being discharged from the compression moulding machine. The short fibre mat was later placed in between two thin layers of POM in a mould cavity and was further taken into the compression moulding machine for preheating. The mould was then preheated for approximately 5 min, and compressed at a temperature of 200^{o}C with a pressure of 130 MPa for 15 minutes. At that stage, the mould was cool to nearly 80^{o}C under pressure before being discharged from the compression moulding machine. The parameters mentioned above were also used in the production of continuous POM/kenaf where kenaf yarns are placed in between two layers of POM followed by compression moulding at 200^{o}C. Samples for tensile, flexural and impact tests were isolated and prepared for testing according to ASTM standards mentioned earlier. It is important to note that the processing temperature used in the production of the composites was kept at 200^{o}C throughout the production process to achieve good wetting and avoid the degradation of kenaf fibre which usually starts at temperatures above 200^{o}C [6].

2.4 Production of short and continuous POM/kenaf/PET hybrid composite

Prior to the production process, the mould was prepared by scraping the surfaces and edges of the mould cavity to remove stains of other materials that may mix with the composite during production. Subsequently, the continuous kenaf, and PET yarns were placed in between two thin layers of POM in the mould cavity and was then taken into the compression molding machine where it is being preheated before compression. It was then compressed for approximately 25 minutes at a temperature of 200^{o}C and with a pressure of 130 MPa. At that stage, the mould was allowed to cool under pressure to nearly 80^{o}C before being discharged from the compression molding machine.

2.5 Mechanical testing

Tensile tests were conducted according ASTM D638 of testing thermoplastic composites. Approximately 10 specimens were subjected to tensile loading along the fibre direction and the fractured surfaces of the specimens after the tests were observed under SEM to study the morphology of the fibres with respect to the matrix. A three point bending test was conducted according to ASTM D790 for testing polymer composites. The specimens were simply supported on a Jig of a universal material testing machine and were loaded in such a way that the compressive stress occurs in the upper portion of the specimen while the tensile load occur in the lower portion, consecutively. A notched Charpy impact test was conducted according to ASTM D6110 of testing polymer composites. Approximately 20 samples were tested for each composition to determine the impact energy absorbed and dissipated by each specimen. In general, failure of the composites during tensile and impact test was characterized by fibre pullout and matrix cracking while the failure of the composites during flexural test can be attributed to delamination of the fibres due to the effect of shear force produced by the loading nose during the three point bending tests.

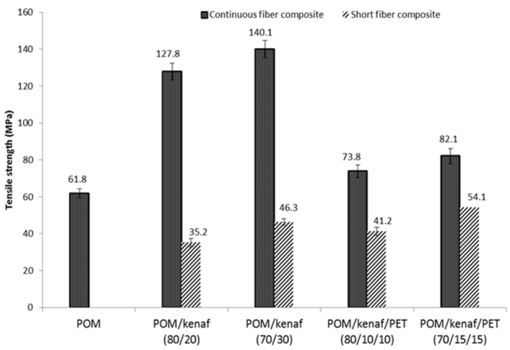

Fig. 4: Results of tensile strengths of short and continuous fibre composites

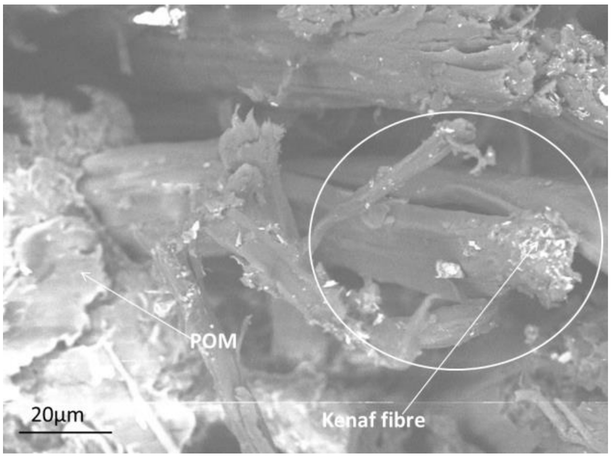

Fig. 5: Interfacial bonding between kenaf fibre and POM

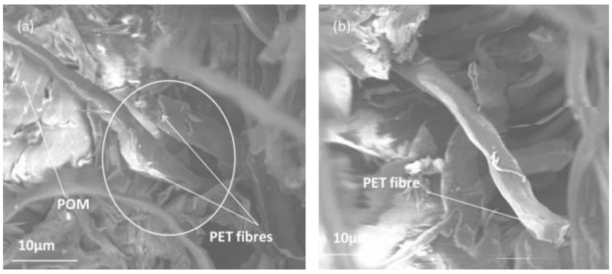

Fig. 6: Interfacial bonding between PET fibre and POM

2.6 Determination of void content

The void content of the composites was determined using the specifications given in ASTM D2734. In this method, the density of POM, kenaf, and PET fibres were measured independently prior to the production of composites. Afterwards, the weight percentage of POM and the reinforcements were measured, and the theoretical density calculated using the following equation:

$$T = \frac{100}{\left(\frac{R}{D} + \frac{r_k}{d_k} + \frac{r_p}{d_p}\right)} \quad (1)$$

Where, T is the theoretical density (g/cm^3), R is the weight percentage of POM in the composite (%), D indicates the density of POM (g/cm^3), r_k is the weigh percentage of kenaf in the composite (%), d_k denotes density of kenaf fibre (g/cm^3), r_p is the weight percentage of PET fibre (%) and d_p is the density of PET fibre (g/cm^3). After the theoretical density was calculated, the experimental density of the composite was determined using a densimeter, according to the specifications and guidelines given in ASTM D792. Subsequently, the void content of the composite was calculated using the following equation:

$$V = 100\,\frac{(T_d - M_d)}{T_d} \qquad (2)$$

Where, V is the void content of the composite (%), T_d is the theoretical density and M_d is the measured density of the composite (g/cm^3).

3. RESULTS AND DISCUSSION

3.1 Tensile properties

It is important to note that the tensile properties of the composites strongly depend on the individual constituent material and fibre distribution in the matrix. Kenaf fibre has a higher elastic modulus compared to PET fibre while PET fibre has a higher tensile strength with respect to kenaf fibre. Assuming perfect bonding between the fibres and the matrix, the combination of these properties is expected to produce a composite with high strength and elastic modulus. However, the tensile strength of the hybrid composite is lower compared to kenaf fibre composite due to weak interfacial bonding between PET fibre and POM. This may be attributed to insufficient wetting of PET fibre by POM. Failure of the hybrid composite during a tensile test can be characterized by fibre pullout. On the other hand, kenaf fibre composite failure was characterized by fibre breakage due to good adhesive bonding with POM matrix.

The results of tensile strength of short and continuous fibre composites are shown in Fig. 4. It can be observed that the tensile strength of short POM/kenaf (80/20) composite dropped by approximately 43% from 61.8 MPa to 35.2 MPa compared to neat POM. Similarly, the tensile strength of short POM/kenaf/PET (80/10/10) dropped by nearly 33% from 61.8 MPa to 41.3 MPa compared to neat POM. The results indicate an adverse effect on tensile strength of the composites and may be due to frequent fibre ends of short fibres in the composite. It may also be due to the mechanics of load transfer in short fibre composites where the load is being shared between fibre and matrix as demonstrated by the SEM micrograph in Fig. 5 [14, 15]. Furthermore, increasing the PET fibre content improved the composite tensile strength as depicted in Fig. 4 and the SEM micrograph in Figs. 6a and 6b also illustrates the bonding between PET fiber and POM. It can be said that the contribution of fibres in composites is maximum only when the fibres are parallel to the loading axis. The extent at which the strength and stiffness will reduce strongly depends on the angle of the fibres to the loading axis and the number of fibres that are mis-oriented to the loading direction. From the SEM micrograph in Figs. 6a and 6b, the fibres can be observed projecting out from the matrix, suggesting poor interfacial bonding due to low surface energy of the fibre with respect to the matrix as described by another researcher [16]. Micro cracks were also observed at various sections of the composites.

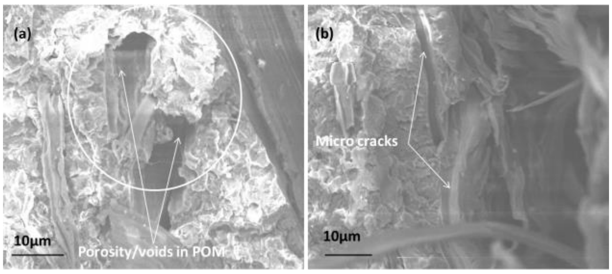

Fig. 7: Porosity and micro-cracks in composites

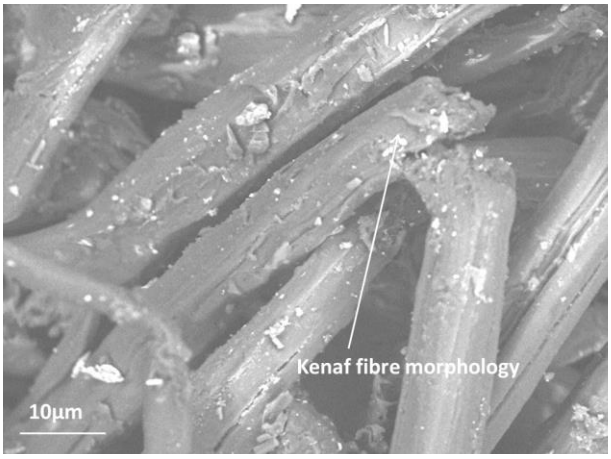

Fig. 8: Kenaf fibre morphology

This may be ascribed to poor wetting of the fibres by the matrix as depicted in Figs. 7a and 7b. However, the results in Fig. 4 show a substantial increase in tensile strength of continuous POM/kenaf composites by approximately 127% and 107% for 70/30 and 80/20 compositions, respectively. These enhancements are most

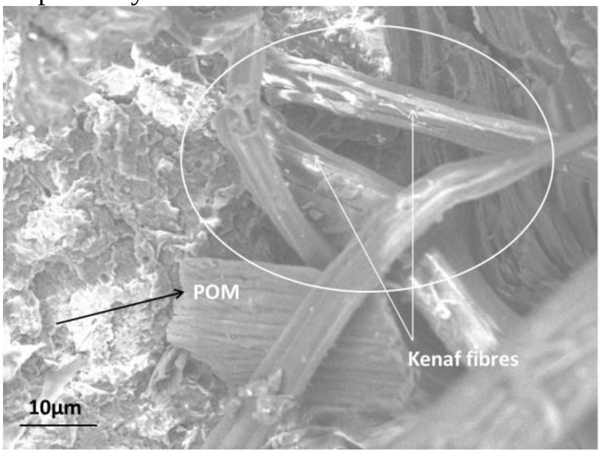

Fig. 9: Interfacial adhesion between kenaf fibre and POM

probably due to good interfacial bonding between kenaf and POM matrix as demonstrated by the SEM micrograph in Figs. 8 and 9 [17, 18]. Moreover, tensile strength of POM/kenaf/PET hybrid composites reduced by 33% and 19% in 70/15/15 and 80/10/10 compositions, respectively. The results suggest weak bonding between PET fibre and POM, which may be due to slight differences in their respective surface energy. For good interfacial bonding to occur between fibre and matrix, the surface energy of the reinforcing fibre should be significantly higher than the surface energy of the matrix [19, 20]. The theory of composite mechanics has shown that in continuous fibre composites when an external load is applied parallel to the fibre direction, both fibre and matrix will be stretched along that direction with equal strain [21]. Since the fibre is much stronger and stiffer than the matrix, it will take the larger stress; hence, the composite strength will be much depended on fibre strength. However, when discontinuous fibres are randomly oriented in a matrix, the assumption of equal strain on application of an axial load parallel to the fibre direction no longer holds since the stress on the fibres tends to fall off towards their ends in the composite. The principle illustrates that the load is being transferred from fibre to matrix. Therefore, the lower strength of the fibres and the average higher strength of the matrix may eventually weaken the composite. This theory clearly explained why there was a drop in tensile strength of the randomly oriented short fibre composites.

Fig. 10 shows the elastic modulus of the short and continuous fibre composites. There was substantial improvement in the elastic modulus of the short fibre composites compared to neat POM. High elastic modulus of kenaf and PET fibre accounted for the increase in the elastic modulus of the composites which indicates that the kenaf fibre undergo more transverse strain than the PET fibre

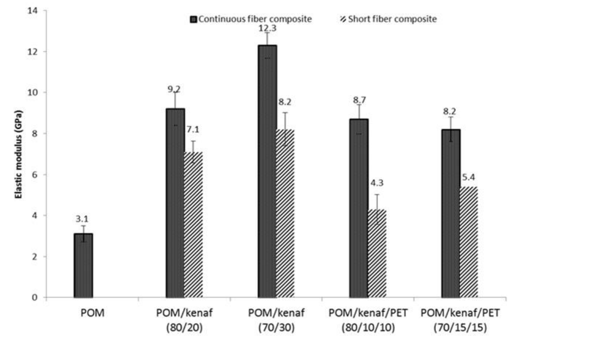

Fig. 10: Results of elastic modulus of the short and continuous fibre composites

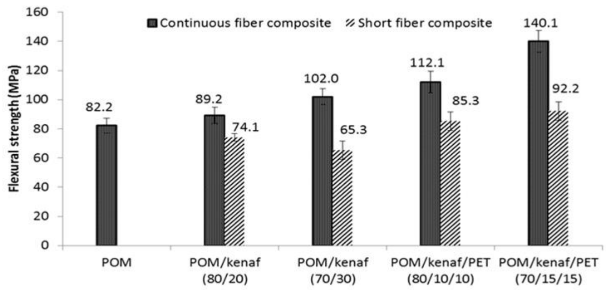

Fig. 11: Results of flexural strength of the short and continuous fibre composites

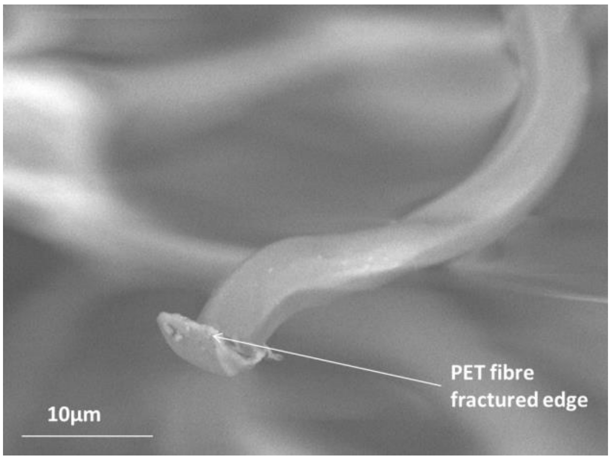

Fig. 12: Morphology of kenaf fibre after flexural test

in the hybrid composite. The results also show that the elastic modulus of continuous POM/kenaf (70/30) composite increased by nearly 34% compared to continuous POM/kenaf (70/30) composite. A similar trend can be observed in the hybrid composite where the elastic modulus of POM/kenaf/PET (70/15/15) increased by approximately 35%.

3.2 Flexural properties

The flexural properties of the composites are the combined effect of composite tensile, compressive and shear properties. High elastic fibres, usually contributes to composites flexural strength. Fig. 11 shows flexural strengths of the short and continuous kenaf fibre composites. The results revealed the flexural strength of short POM/kenaf (70/30) composite slightly dropped by nearly 20% compared to neat POM. However, the flexural strength of POM/kenaf/PET (70/15/15) hybrid composite marginally increased by approximately 12.2% from 82.2 MPa to 92.2 MPa compared to neat POM. This may be due to the addition of PET fibre in the composite which has a higher flexural strength than kenaf fibre. Another trend that can be observed in short POM/kenaf (80/20) where the flexural strength dropped by almost 10% compared to neat POM. Fig. 11 also shows the flexural strengths of the continuous fibre composites. The flexural strength of continuous POM/kenaf (70/30) composite improved significantly by approximately 20% from 82.2 MPa to 102.0 MPa compared to neat POM. A similar trend can be observed in the hybrid composite where POM/kenaf/PET (70/15/15) shows a significant improvement by approximately 42% from 82.2 MPa to 140.1 MPa with respect to neat POM. This significant increase may be due to hybridization with PET fibre that resulted in high deflection angle during the flexural test [22, 23]. Compared to short fibre composites, the flexural strength of the continuous fibre composites is higher as illustrated in Fig. 11. The SEM micrograph in Fig. 12 shows kenaf fiber breakage in the composite after the flexural test. This may be attributed to micro cracks initiation and propagation in the composite with high risk of fibre debonding and weak interfacial adhesion. The micro cracks in the composite can create a larger surface area that may lead to low flexural strengths of the composite as reported by another researcher [24]. This is expected due to weak interfacial bonding between the polar natural fibre and the non-polar thermoplastic matrix.

The flexural modulus of the composites may depend on the stiffness of the high elastic modulus fibre.The flexural moduli of the composites are shown in Fig. 13. The flexural modulus of short POM/kenaf/PET (70/15/15) composite improved by approximately 41% from 2.3 GPa to 3.9 GPa. Likewise, the flexural modulus of POM/kenaf (70/30) increased by nearly 30% from 2.2 GPa to 3.3 GPa compared to neat POM. The results clearly show the influence of hybridization where PET fibre significantly improved the flexural moduli of the composites [25, 26]. The flexural modulus of continuous POM/kenaf (70/30) hybrid composite increased by approximately 29% compared to neat POM as illustrated in Fig. 13. Similarly, the flexural modulus of POM/kenaf/PET (70/15/15) increased by approximately 40% with respect to neat POM. Compared to short fibre hybrid composite, the flexural modulus of the continuous fibre composites slightly dropped due to the high deflection angle from the specimen's equilibrium position.

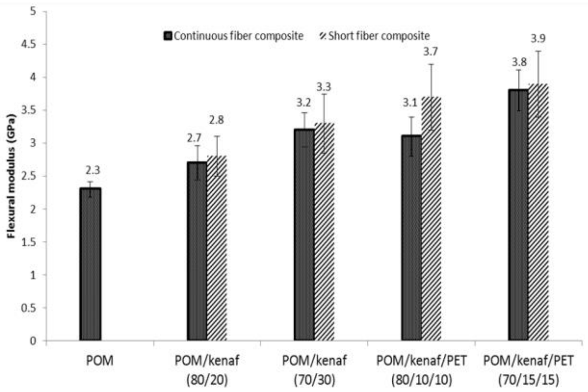

Fig. 13: Results of flexural modulus of the short and continuous fibre composites

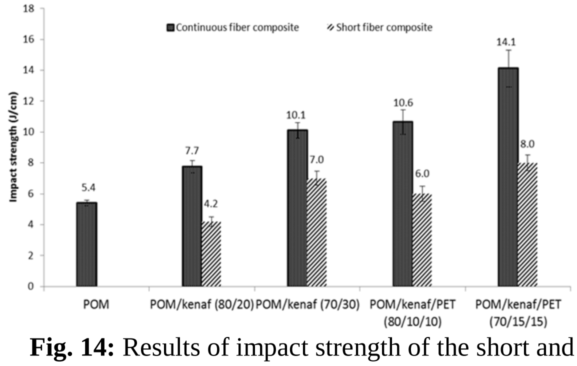

Fig. 14: Results of impact strength of the short and continuous fibre composites

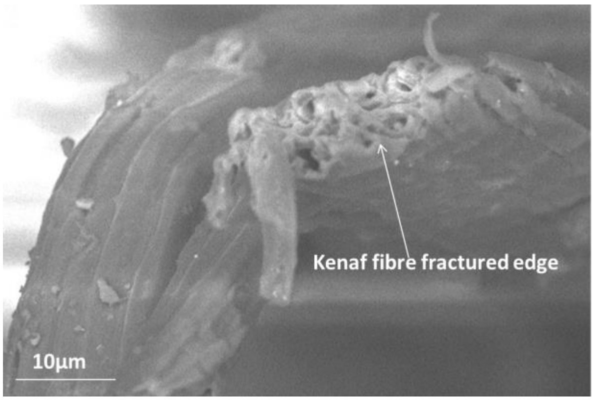

Fig. 15: Fractured edge of kenaf fibre in the composite

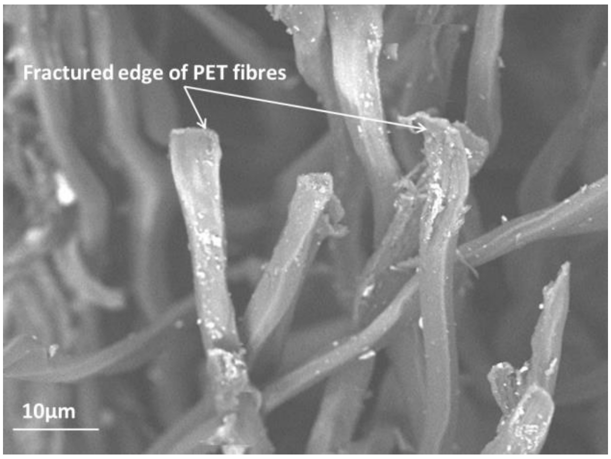

Fig. 16: Fractured edges of PET fibre in the composite

3.3 Impact strength

The impact strength of the composites depends on the energy require to propagate a crack through the composite cross-section and energy require to cause delamination between the fiber and matrix, and it is determined from the differences in potential energy before and after the impact test. A substantial improvement of almost 48% from 5.4 J/cm to 8.0 J/cm was observed for short POM/kenaf/PET (70/15/15) hybrid composite compared to neat POM as shown in Fig. 14. A similar trend of results was observed by other researchers where an increase in fibre content, significantly improved the impact strength of hybrid composites [27-29]. Therefore, it can be said that hybridization with PET fibre, significantly increased the composite impact strength. This enhancement indicates that kenaf fibre has poor damage resistance capability compared to PET fibre in the hybrid composite. The SEM micrograph in Figs. 15 and 16 shows deformation and failure mechanisms that resulted in toughness enhancement in the composites. Such failure mechanisms include energy dissipation by sliding of fibres, fibre deformation that leads to micro-cracking, fibre pullout, buckling, fracture and tearing as described by another researcher [27]. This may be attributed to low impact energy of kenaf fibre with respect to PET fiber and mechanics of load transfer at fibre-matrix interphase. In the continuous fibre composites, improvement can be seen across the board for both POM/kenaf composite and POM/kenaf/PET hybrid composite. The high impact strength improvement was 161% for POM/kenaf/PET (70/15/15) hybrid composite while the lowest was 30% for POM/kenaf (80/20) composite compared to neat POM. The composites with 30% reinforcement, show a ductile fracture behavior whereas those with 20% fibre content demonstrate brittle fracture behavior. A possible explanation is that an increase in fibre content, improves the composites ductility. The matrix also plays a significant role in improving the composites impacts strength since its function is not only limited to binding the fibres together, but also to absorb and transmit impact energy to the fibres [30].

3.4 Void Content

The determination of void content is essential in this study since it has a detrimental effect on the mechanical properties of the composites such as tensile, flexural and impact strengths. Higher void content can also lead to environmental degradation, scatter in strength properties and weak interfacial bonding between fibre and matrix. The results of void content of the short and continuous fiibre composites are presented in Fig. 17. Compared to the short fiber composite, the percentage void content in the continuous fibre composites is slightly lower in the POM/kenaf composition. However, the percentage void content of continuous POM/kenaf/PET (80/10/10) hybrid composite marginally increased by approximately 6% compared to the short fiber composite. A possible explanation is that the presence of micro cracks in the composite, accounted for the increase in voids and large surface area of the fibre-matrix interphase.

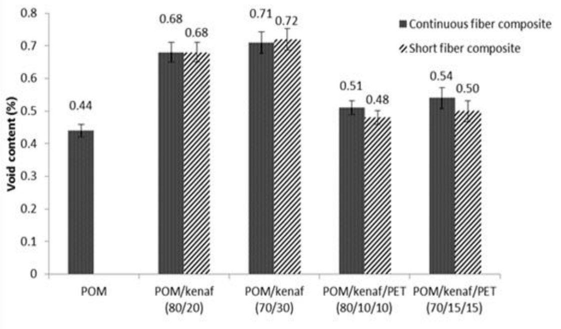

Fig. 17: Results of void content of the short and continuous fibre composites

4. CONCLUSIONS

The mechanical properties of short and continuous kenaf fibre reinforced POM composite was studied with respect to fibre loading and the influence of hybridization. The tensile strength of short POM/kenaf (80/20) composite dropped below that of neat POM by approximately 43%. Likewise, the tensile strength of POM/kenaf/PET (80/10/10) dropped by 33% from 61.8 MPa to 41.3 MPa compared to neat POM. The tensile strength of continuous POM/kenaf composite improved significantly by approximately 127% and 107% for 70/30 and 80/20 compositions. The tensile strength of the hybrid composite (POM/kenaf/PET) reduced to 33% and 19% for 70/15/15 and 80/10/10 compositions compared to their respective POM/kenaf composites. Flexural strength improved by approximately 12.2% for short POM/kenaf/PET (70/15/15) composition compared to neat POM. The flexural strength of continuous POM/kenaf (70/30) composite improved significantly by approximately 20%. A significant improvement of 48% in impact strength was observed for POM/kenaf/PET (70/15/15) hybrid composite compared to neat POM. The high impact strength improvement was 161% in continuous POM/kenaf/PET (70/15/15) hybrid composite while the lowest was 30% in POM/kenaf (80/20) composite compared to neat POM. Finally, the results of the investigation confirmed that the mechanical properties of continuous kenaf fibre reinforced POM are superior to the short fibre composites due to mechanics of load transfer at fibre-matrix interphase.

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ABBREVIATIONS	**DEFINITION**
ASTM	American Society for Testing and Materials
HDPE	High Density Polyethylene
MAH	Maleic anhydride
MFI	Melt Flow Index
PET	Polyethylene terephthalate
PLA	Polylactic acid
POM	Polyoxymethylene
PP	Polypropylene
SEM	Scanning Electron Microscopy
WPE	(Waste –polyethylene)

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