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Engineered Material from Natural Fibre for Interior Design Applications

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ABSTRACT

Some natural fibres including jute, flax, hemp, kenaf and sisal have been found very promising for potential applications as reinforcement in engineered composite materials. The environmental drivers, such as ability to absorb CO_2 during production in contrary to synthetic materials and having non-toxic characteristics, have made them ideal candidates for incorporation into composites for industrial and technical applications that do not require very high mechanical resistance, for examples, window and doorframes, indoor furniture panels, automotive panels and upholstery, parcel shelves, noise insulating panels etc. This paper discusses fabrication and mechanical performance testing of multi-layered jute fabrics reinforced thermoplastic composite material. Jute hessian fabrics were sandwiched in 0° orientation into several layers of High Density Polyethylene (HDPE) polymeric sheets and pressed at high temperature and pressure to form composite laminates. Microscopic analysis revealed that the fibre and yarn orientation of fabrics within composite remained intact and no visible void was identified. Mechanical performance of the composites having a small percentage of fibre content was found to have improved significantly when compared to the pure HDPE laminates. The tensile and flexural strength of the laminate composite with optimum number of layers (6-layer makes a weight fraction of 18.50%) were improved by more than 50%, while flexural modulus was also increased significantly. Fracture morphology of the composite investigated by a Scanning Electron Microscope (SEM) showed good adhesion of the jute fabrics with the polymer matrices.

KEYWORDS

Natural Fibre, Jute fabric, High Density Poly Ethylene (HDPE), Composite, Laminate, Mechanical properties

1. INTRODUCTION

Jute is categorised as a bast fibre obtained from the stem of plants that belong to the species of *Corchorus capsularis* (white jute) and *Corchorus olitorius* (tossa or dark jute) (IJSG, n.d.; Summerscales et al., 2010). It is the second most important natural fibre after cotton and mostly produced in Bangladesh, India and China (Quarshie and Carruthers, 2014). Like many other natural fibres such as flax, hemp, ramie, sisal and cotton, the chemical constitution of jute fibre is dominated by cellulose (over 61-71.5%) (Kabir et al., 2012), which is a polysaccharide consisting of a linear chain of several hundred to many thousands of $\beta(1\rightarrow4)$ linked D-glucose units. However, its chemical composition is specially characterised by the presence of Hemicellulose (13.6-20.4%) and exceptionally high content of lignin (12-13%), and therefore, is identified as a lignocellulosic fibre. Some of the natural fibres including jute, flax, hemp, kenaf and sisal have been experimented in the last few decades for potential applications as reinforcement in engineered composite materials and have been found very promising. These fibres have good strength and stiffness, whilst being significantly lighter in weight than the conventional reinforcements such as glass fibre. Although tensile strength of the jute fibres is lower than that of glass fibre, their density is approximately the half, therefore the specific moduli is higher, and tensile modulus is roughly similar to the glass fibre (Quarshie and Carruthers, 2014; Kabir et al., 2012). Additionally, from the environmental point of view, jute as a natural fibre from plants that absorb CO_2 during production in contrary to the synthetic materials, and its non-toxicity have made them ideal candidates in developing composites for industrial and technical applications that do not require very high mechanical resistance such as window and doorframes, indoor furniture panels, automotive panels and upholstery, parcel shelves and noise insulating panels etc. (Mantia and Morreale, 2011). The most notable example of natural fibre reinforced polymeric composite is the jute-based thermoplastic door panels produced and commercialised by German automaker Mercedes-Benz in the 90s (Mantia and Morreale, 2011; and Summerscales et al., 2010).

Jute has been applied in all possible different forms, such as fibre (Bisaria et al., 2015; Gopinath et al., 2014), sliver (Das & Bhowmick, 2015), yarn (Memon and Nakaib, 2013; Pujari et el. 2015), woven (Sudha & Thilagavathi, 2015; Arju et al., 2015), knitted fabrics (Arju et al., 2015) and non-woven sheets (Karaduman et al., 2014; Sayeed et al., 2013) in composite manufacturing using either thermoplastic (Sayeed et al., 2013) or thermoset polymeric matrices (Bisaria et al., 2015; Das & Bhowmick, 2015; Pujari et el. 2015). Hydaruzzaman et al. (2010) treated bleached fabric of tossa jute with a solution of 50-90% oligomer urethane acrylate, 2% photo-initiator in methanol, and irradiated under UV light for 24 hours before heat pressing five layers of treated fabrics to form composite laminate. They identified the best mechanical properties from the composite that was made from jute fabrics treated with 70% of oligomer, 28% methanol and 2% photo-initiator followed by UV radiation. Kafi et al. (2011) prepared multi-layered jute-polyester composite after atmospheric plasma treatment of jute fabrics and found improvements in flexural strength and modulus and inter-laminar shear stress. Khan et al. (2012) prepared composite by compression molding of four layers of hessian fabrics within five layers of PVC and found the composite containing 40% fibre showed the best performance. An increase in tensile, flexural and interlaminar shearing strength was observed by Seki et al. (2012) in composite made from alkali and oligomer siloxane treated single layer of jute fabric compression molded into two layers of high-density polyethylene (HDPE). Zaman et al. (2012) varied the concentration of urethane acrylate oligomer including photo-initiator for pre-treating bleached hessian fabric and UV radiated for 24 hours for preparing thermoset laminate from five layers of treated jute fabrics through compression molding. They found best results from 70% oligomer treated fabrics. Khan et al. (2013) discussed an ecofriendly bio-composite made by compression molding of single layer of jute fabrics sandwiched between poly (L-lactic acid) (PLLA) films. Berhanu (2014) sandwiched two layers of jute fabrics between three layers of polypropylene sheets and made thermoplastic composites by hot pressing. They reported significant enhancement of mechanical properties of jute-reinforced composites with the increase of fibre content up to 40% (in weight). Sudha and Thilagavathi (2015) reported a jute-vinylester composite material by compression molding of four layers of alkali treated jute fabrics (16 EPI & 13 PPI; 430 GSM) impregnated with a solution of vinylester resin, catalyst and accelerator. Arju et al. (2015) prepared jute reinforced polypropylene composites from single layer of plain (1/1, EPI 10-12 & PPI 10-12) and twill (2/1, EPI 18-20 and PPI 9-10) fabric structures separately sandwiched between two layers of polypropylene sheets and found that the composites having twill structured fabric displayed higher tensile strength than the composites with the plain fabrics.

Current literature shows that very little work was carried out on developing multilayer laminate with jute fabrics and High Density Polyethylene (HDPE). As HDPE is mechanically less stronger than the commonly used other polymers such as polypropylene, any improvement of HDPE by reinforcing with natural fibres be significantly advantageous from structural application point of view. This paper aims to develop multi-layered HDPE composite laminates reinforced with hessian jute fabrics and to investigate its mechanical properties and interfacial characteristics. Laminate composites were prepared by varying the number of jute fabric layers within a nominal laminate thickness of 6.5 mm. The composite fabricated in this work is targeted for interior design applications.

2. MATERIALS AND EXPERIMENTAL METHOD

2.1. Raw Materials

A 100% hessian fabric made of tossa jute from Janata Jute Mills Ltd., Bangladesh was used as a filler material for manufacturing laminated composites. The specification of the jute fabric has been evaluated through visual inspection and tests and presented in Table 1. Structure of the jute fabric (i.e. EPI & PPI) and weight (GSM) were determined following the standards BS EN 1049-2:1994 and BS 2471:2005 respectively. The breaking strength and elongation of the fabric were analysed following the test standard BS ENISO 13934 and using "Testometric Micro 500" (UK) testing machine. Fibre orientation within the jute fabric was investigated using an optical microscope. HDPE films with a thickness of 1 mm were collected from Direct Plastics Ltd, Sheffield, UK and the general specification of the sheet is given in Table 2.

Table 1. Specification of Jute fabrics

Parameters	**Value**	**Unit**
Weave design	1/1 (plain)	-
Weight	209	GSM
Warp (EPI)	10	-
Wept (PPI)	9	-
Average Breaking Strength Warp	432.9	Newton
Average Breaking Strength Weft	330.9	Newton
Average Breaking Extension Warp	13.31	mm
%Average Breaking Extension Warp	6.7	%
Average Breaking Extension Weft	11.81	mm
%Average Breaking Extension Weft	5.9	%

Table 2. Specification of HDPE films

Parameters	Value	Unit
Colour	Natural	-
Density	0.947	g/cm³
Tensile Strength at yield	25	MPa
Shore D hardness	64	-
Crystalline melting point	130	°C

2.2. Composite Fabrication

Jute fabrics were cut into square pieces of 175 mm × 175 mm dimension and then placed in an oven at 105 °C for 40 minutes to remove moisture. HDPE sheets were also cut into the same dimensions to form the laminate plate with alternate layer of jute and HDPE. Three different types of composite laminates were fabricated using 2, 4 and 6 jute layers along with one pure HDPE laminate. Fig. 1 shows a design of 6 jute layers stacked at 0° orientation in warp direction between seven layers of HDPE sheets. For 2-layer design, three HDPE sheets were placed at both top and bottom and two jute fabrics were positioned in the middle separated by one HDPE sheet. Similarly, for the 4-layer design, two HDPE sheets were placed at both top and bottom and four jute fabrics were in the middle separated by three HDPE sheets. Dry jute fabrics taken out from the oven were first weighed and immediately stacked in between the HDPE layers according to the designs and placed in a steel die of 177 mm × 177 mm × 6.5 mm to minimise absorption of moisture by the jute fabrics from the laboratory environment. The stacked materials in the die were placed between two steel plates and hot pressed in a compression moulding machine (Bradley & Turton Ltd., Kidderminster, UK) as shown in Fig. 2(a) at 195°C for 20 min under a load of 412 KN. Then the composite laminate with the die was cooled to room temperature using another water-cooled press under pressure for 10 mins (Francis Shaw & Co., Manchester, UK). Finally, the laminate was taken out from the die (Fig. 2b), weighed for weight fraction calculation and cut into a desired width of 20 mm in warp direction (Fig. 2c) by a vertical bandsaw machine for conducting mechanical tests. The samples were deburred and polished in a grinding machine to remove any stress rising points. Pure HDPE laminates of same dimensions were also prepared following the same procedure. Jute fabric weight fraction in the laminates were calculated from laminate and fabric weights. It was found that the laminates with 2 (L2 composite), 4 (L4 composite) and 6 (L6 composite) jute layers contain approximately 6.70 wt%, 12.90 wt%, and 18.50 wt% of jute fibres respectively.

Fig. 1. 6-layer Jute-HDPE composite design

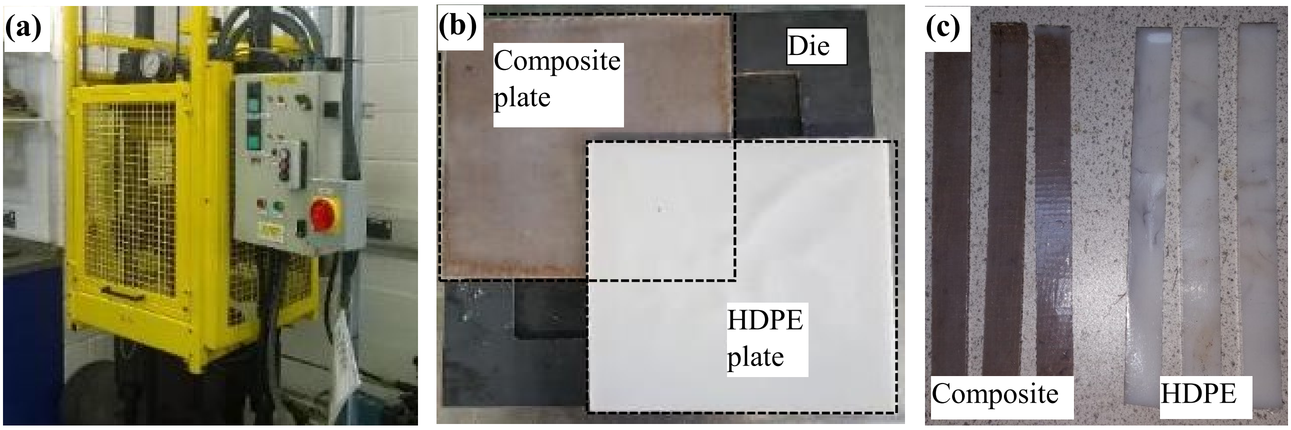

Fig. 2. (a) Compression moulding machine (b) prepared composite and HDPE plates with die and (c) samples for mechanical testing

2.3. Mechanical Testing

Tensile tests of Jute-HDPE and HDPE only samples were carried out on Hounsfield H10 KS Tensometer, UK testing machine equipped with a 10,000 N load cell, according to ASTM D-3039. The cross-head speed used for the tensile specimens was 50 mm/min. System control and data analysis were preformed using Qmat 5 software system. At least three samples with a nominal dimension of 177 mm × 20 mm × 6.5 mm (length × width × thickness) for each type of composite laminates were tested to check repeatability in the test results. However, the dimensions of individual test samples were measured and entered into the software for the accurate measurement of strength. The tensile tests of the composite samples were conducted along the warp direction of the jute fabric as tensile loading in that direction generally shows higher strength owing to the higher yarn density. The flexural strength and modulus of the Jute-HDPE composite and HDPE plate were measured using a three-point bending test according to ISO 178:2010/ ASTM D790-02: 2002 in the same machine (Hounsfield H10 KS Tensometer, UK). The tests were carried out with a span-to-depth ratio of 16:1 and at a crosshead speed of 5 mm/min. The experimental set-ups with the samples for tensile and flexural tests are presented in Fig. 3.

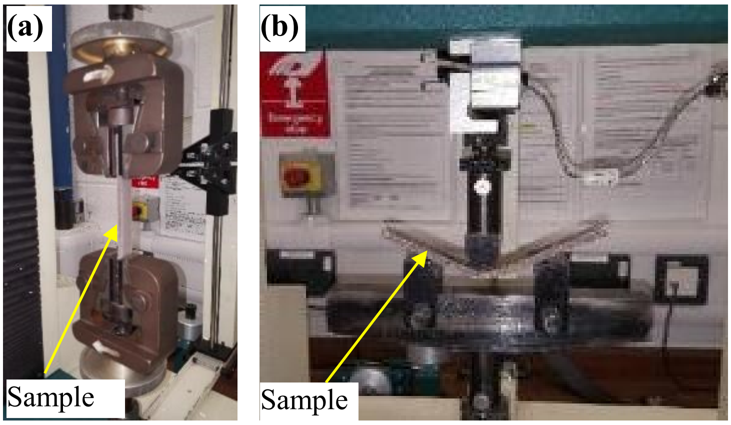

Fig. 3. Experimental set-ups for (a) tensile test and (b) flexural test

2.4. Microscopic Observation

The top view and side view of the composite samples were observed in an optical microscope to check the jute yarn orientation and layer positions within the composite. The cut and fracture surfaces of the Jute-HDPE composite were also observed under a scanning electron microscope (SEM) to analyse the adhesion and interfacial characteristics between jute fabric and HDPE. An SEM of model JSM-5600LV from JEOL Ltd. was used at an accelerating voltage equal to 20 kV in the secondary electron mode. The surfaces of the composite samples were coated with gold by means of a plasma sputtering apparatus prior to the SEM observation as the samples are non-conductive.

3. RESULTS AND DISCUSSIONS

3.1. Characteristics of Jute Fabric

From the specification of the jute fabric used in this work, it was clear that the number of yarns in warp direction was more than that in the weft direction. The tests showed that the average fabric strength was higher (432.9 N) in the warp direction. Although the weave design (1/1- Plain) was visible in the naked eye, the optical microscopic view clearly shows the fibre bundles in individual yarns (Fig. 4).

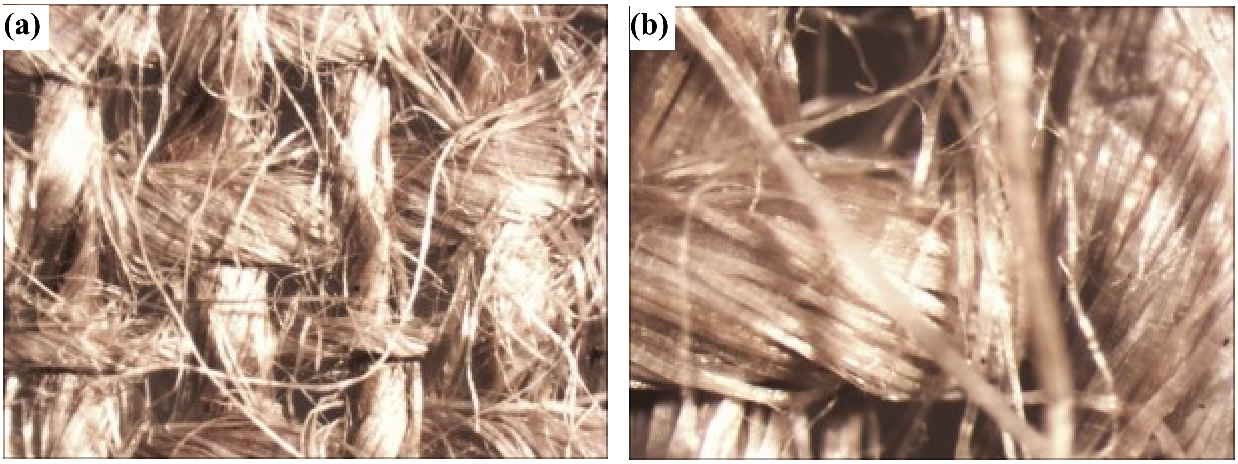

Fig. 4. Magnified views of (a) jute fabric and (b) jute fibres

3.2. Physical Characteristics of Composite

Fig. 5 presents the top view of jute reinforced HDPE composite laminate. Yarn orientation of the jute fabrics and space between yarns remained unchanged in the prepared composite as compared to the jute fabric. However, in some cases the fabric in the bottom side of the laminate was slightly stretched in the middle and compressed near the edge possibly due to small movement between the die and compression plates while applying the pressure in the moulding machine.

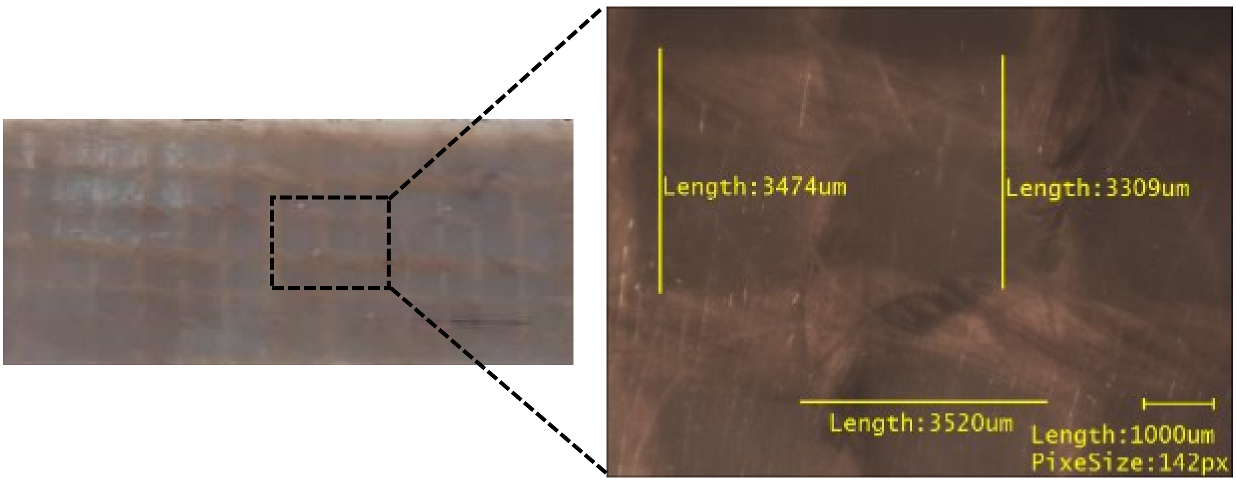

Fig. 5. Top surface views of jute-HDPE composite under an optical microscope

The polished cross-sectional view of the sample revealed that the layers of the jute fabrics were also evenly spaced in the HDPE matrix even after high compression moulding process (Fig. 6a). No visible voids were present across the thickness of the sample even at high magnification and the layers were completely immersed within the matrix. The magnified view of a yarn (Fig. 6b) shows that it was flattened in the matrix due to the high moulding pressure and the polymer material flowed into the yarn. At this magnification, the extent of polymer flown around the fibres in the yarn was not very clear. However, at further higher magnification, it was revealed that even at this higher pressure the melt polymer could not wet all fibres uniformly in the yarn, which left differential gaps between the fibres as shown in Fig. 7.

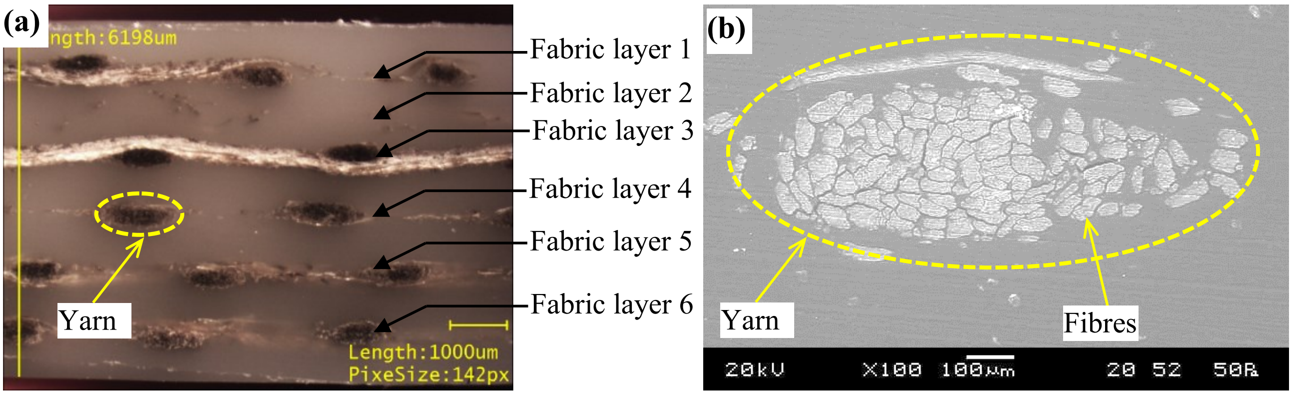

Fig. 6. Cross-sectional view of Jute-HDPE composite: (a) individual fabric layers in the matrix under an optical microscope and (b) a yarn with fibres under an SEM

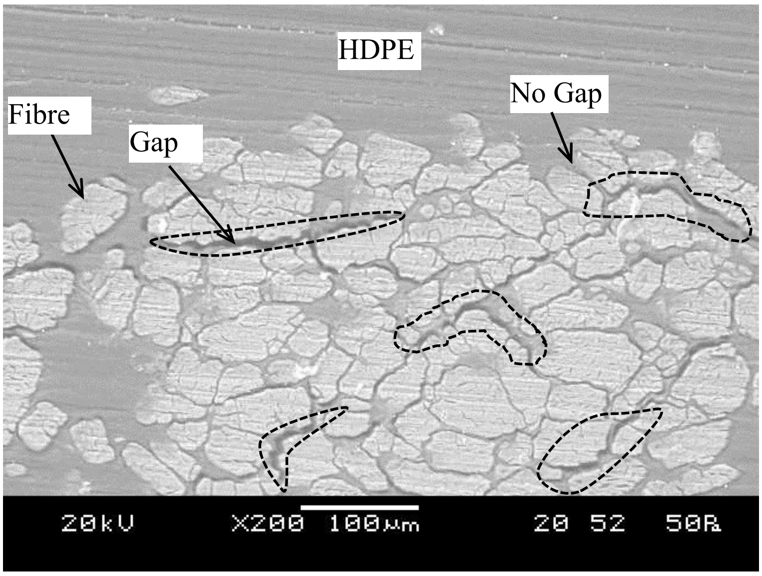

Fig. 7. Cross-sectional view of Jute yarn in HDPE matrix showing gaps between fibres and matrix

Through this study, it has been established that with the current die thickness, maximum six layers can be accommodated in order to maintain a layered structure with substantial distance between the jute layers. Beyond six layers, the layered structure will start to distort through a reduction in gap between the layers and significant amount of HDPE will be squeezed out from the die. Therefore, 6 layers in the laminate has been considered as the optimum number of layers for the die used in this work. The measurement of sample thickness clearly indicated they were thinner than the die thickness by approximately 0.3 mm. This could be due to shrinkage of HDPE material during cooling phase. Periodic waviness was also found on the surface of the laminate plate due to the same reason.

3.3. Mechanical Properties of Composite

3.3.1. Tensile Test Result

Fig. 8. presents the tensile strengths of pure HDPE and the composite materials. The results clearly indicated that in general all layered composites possessed higher tensile strength than the pure HDPE sample. The tensile strength of the HDPE laminate with similar dimension of Jute/HDPE composite was tested as 22.23 MPa, whereas the tensile strengths of 4-layer Jute/HDPE (with 12.9 wt% of Jute) and 6-layers Jute/HDPE (with 18.50 wt% of jute) were found as 26.71 MPa and 36.37 MPa respectively, which was much higher than the findings of Arju et al. (2015) and Seki et al. (2012).

A maximum strength improvement by approximately 62% was achieved with the composite containing six layers of jute fabrics (L6). A tensile strength improvement of 19% was realized with 2-layer composite. However, no significant improvement in tensile strength was found between 2-layer and 4-layer composites. This could be due to a number of reasons such as non-uniform jute layer distribution in the matrix.

Arju et al. (2015) reported tensile strength and modulus of 20.30 MPa and 1.25 GPa respectively for single layer jute fabric reinforced polypropylene composite having 55% weight fraction of jute fibre. Whereas, Seki et al. (2012) identified tensile strength and modulus of 21.2 MPa and 1.21 GPa respectively in untreated single layer jute fabric reinforced HDPE composite having 20% weight fraction. After treating jute fabric with oligomeric siloxane solution, the tensile strength of the Jute/HDPE composite could be improved up to 29.1 MPa and the modulus up to 1.47 GPa. The findings from this work show that layered jute fabrics within HDPE matrix can provide higher tensile strength (36.37 MPa) without any chemical treatment on jute fabrics.

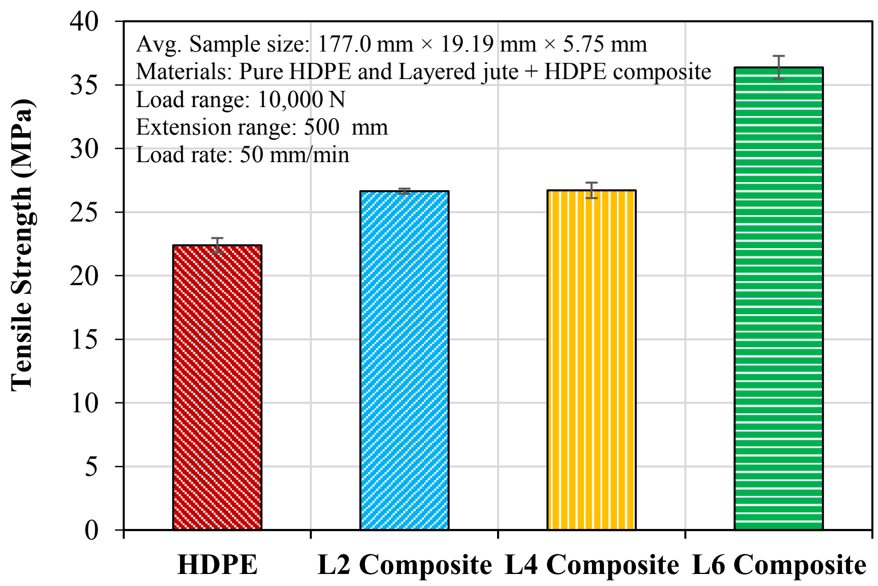

Fig. 8. Tensile strength of pure HDPE and layered jute-HDPE composites in warp direction

3.3.2. Three-point Bending Test Result

Flexural properties of HDPE laminate and jute-HDPE composites are presented in Fig. 9 and Fig. 10. Average flexural strength and modulus of HDPE laminate were tested as 24.84 MPa and 1.165 GPa respectively, whereas the values of 4-layer jute/HDPE composite were found as 29.21 MPa and 1.49 GPA respectively. This means that an increase in flexural strength and modulus by 17.59%

and 63.09% respectively with 4-layer composite when compared to the pure HDPE laminate. Further increase in flexural strength and modulus by 55.72% and 114.9% respectively were found in 6-layer Jute/HDPE composite in comparison to the pure HDPE laminate. Seki et al. (2012) achieved flexural strength of 31.4 MPa and modulus of 0.84 GPa with single layer untreated jute fabric reinforced HDPE composite having 20% weight fraction of jute fibre; and with oligomeric siloxane treatment of jute the values went up to around 46.8 MPa and 1.67 GPa respectively. In this case, for 6-layer Jute/HDPE composites with 18.5 wt% jute, the values of flexural strength and modulus were 38.73 MPa and 2.504 GPa respectively. This indicated that even without any fibre treatment, a significant improvement in flexural strength and modulus can be achieved with more fabric layers in HDPE. However, no significant difference in flexural modulus was found between 2-layer and 4-layer composites. The reason for this is not quite clear yet but further investigation will shade more light to get a better understanding.

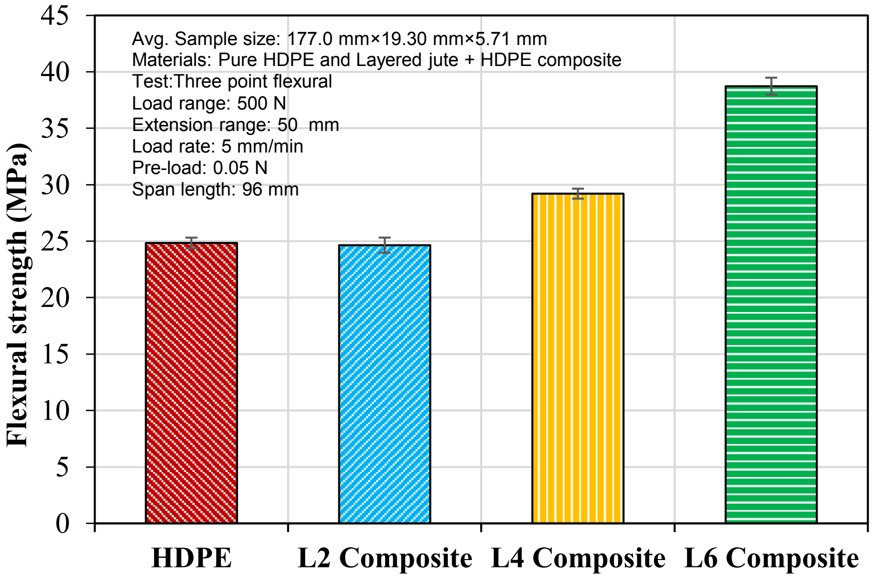

Fig. 9. Comparison of flexural strength of pure HDPE and layered jute-HDPE composites

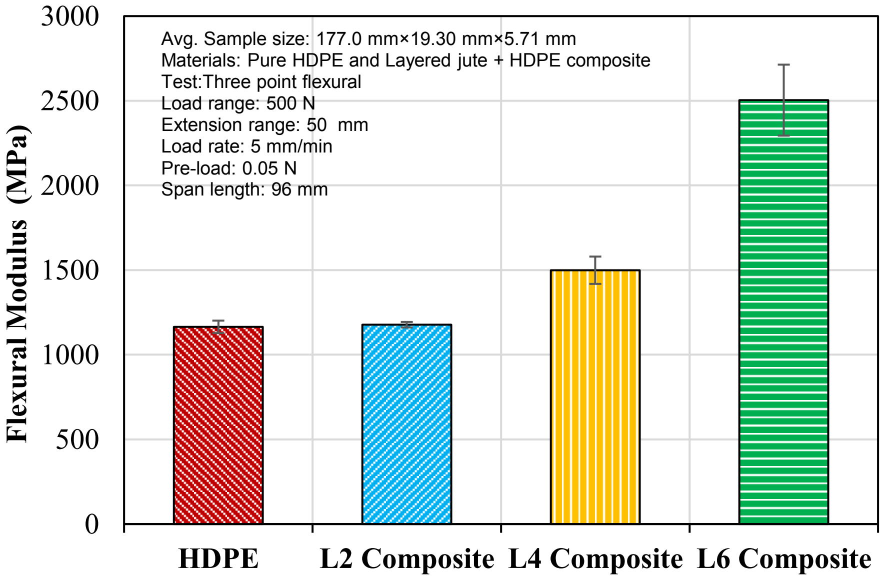

Fig. 10. Comparison of flexural modulus of pure HDPE and layered Jute-HDPE composites

3.4. Interfacial Surface Morphology

The magnified views of the cut surfaces (Fig. 11a,b) showed no void or air gap across the thickness of the composite laminates. HDPE material was well bonded with the yarn of the jute fabric. The good bonding at the interface between jute yarn and HDPE matrix could be the major contributing factor for improved tensile strength found in the composites. However, there was very little evidence of polymer material around the fibres in the yarn. This indicated that the polymer matrix could not reach inside the yarn fully even at high pressure and temperature during compression moulding. Under tensile loading condition, the composite material will start failing via tearing of the fibres in individual yarns as evidenced in Fig. 11(c). In most of the cases, the broken fibre surfaces during tensile failure are free from any adhering polymer. This could be explained by the fact that the matrix material did not firmly adhered onto the individual fibre surfaces. Clean fibre surfaces also indicated extensive interfacial failure owing to the poor fibre/matrix adhesion. At high magnification, a clear gap could be seen between the matrix and a yarn in Fig. 11(d). However, there was some evidences of polymer material adhering with the outer fibres of a yarn (Fig. 11c).

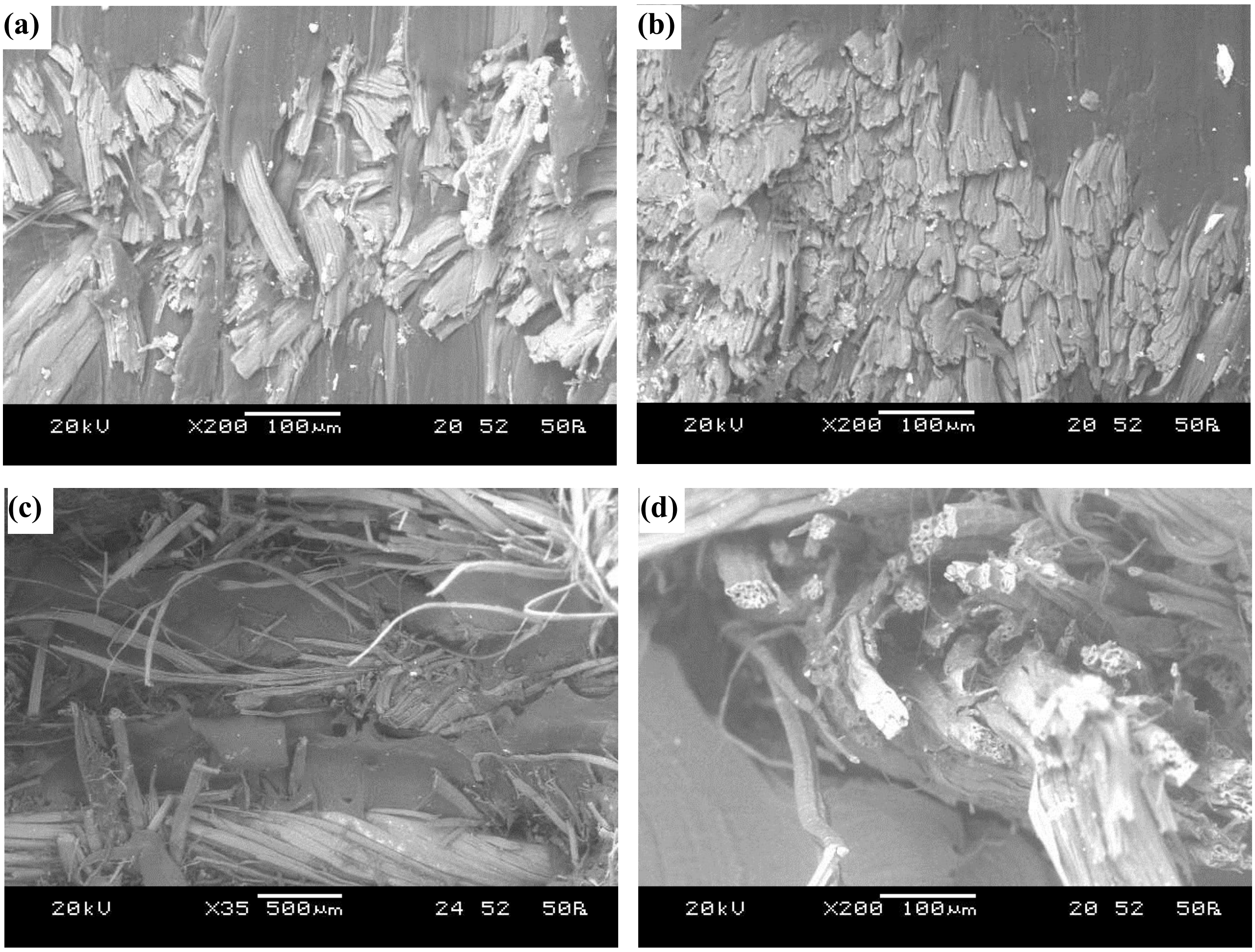

Fig. 11. SEM pictures of (a, b) cut surfaces and (c, d) tensile fractured surfaces

4. CONCLUSIONS

Composites with layered woven jute fabric and HDPE matrix have been successfully fabricated in a hot press (compression moulding machine). Three different types of laminates have been prepared with 2, 4 and 6 layers of jute fabrics within a thickness of approximately 6.2 mm thickness plate. The tests on the jute fabric showed higher strength in the warp direction due to higher number of yarns compared to the weft direction. The visual inspection showed that the jute fabrics at the top surface of the laminate maintained its structure while at the bottom surface, the structure was slightly elongated in the middle and compressed near the edge. The cross-section image of the laminate showed the layers were clearly separated in the HDPE matrix with no voids and good adhesion. It was found that higher volume of jute fabric in the composite displayed the best mechanical properties. For example, tensile strength and flexural strength in the 6-layer composite were improved by approximately 60% and 56% compared to the pure HDPE sample. The cut surface showed good adhesion with the jute fabric in the matrix. However, adhesive failures were observed in the failed samples under tensile loading condition possibly due to inadequate interfacial adhesion.

In future, additional physical and mechanical properties (e.g., impact test) of the composites will be investigated. For further improvement of adhesion between the HDPE matrix and fibre, the effects of chemical treatment on the fibre and addition of coupling agent in between the layers will be explored.

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