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Development and Characterisation of Multilayer Jute Fabric Reinforced HDPE Composites

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ABSTRACT

The bast fibres, a subgroup of natural fibre family, have emerged as a strong competitor of widely used man-made glass fibre for use as fillers or reinforcing materials in certain types of composite materials, which do not require very high mechanical resistance. This paper investigates manufacturing of multi-layered jute fabric reinforced thermoplastic composite and its mechanical performance. Hessian jute fabrics in 2, 4 and 6 layers without any pre-treatment were sandwiched in 0° orientation into seven layers of High-Density Polyethylene (HDPE) sheets and pressed at high temperature and pressure to form composite laminates having three different structural designs. The laminates with 2, 4 and 6 layers contain approximately 6.70 wt%, 12.90 wt%, and 18.50 wt% of jute fibres respectively. Mechanical performance of the composite laminates having 4 and 6 layers of jute fabric was found to have improved significantly when compared to the pure HDPE laminates. Within a given sample thickness of 6.5 mm, the laminate with 6-layers of jute fabric exhibited the best mechanical performance. Optical microscopic analysis revealed that the yarn orientation of the fabrics within the composites remained stable and there was no visible void in the laminate structure. Fracture morphology of the composite investigated by a Scanning Electron Microscope (SEM) showed good adhesion of the jute fabrics with the HDPE matrix.

KEYWORDS

Natural Fibre, Jute, Woven fabric, High-Density Polyethylene (HDPE), Composite, Laminate, Tensile strength, Flexural strength

1. INTRODUCTION

1.1. Natural bast fibre in composites and associated environmental benefits

Fibre-reinforced polymer composite materials have found extensive industrial and household applications in the areas where monolithic materials were employed traditionally [1]. This is now a multimillion-dollar market globally and around 95% of it is shared by the glass fibre reinforced composite (GFRC) [2]. However, some natural fibres, due to their advantages over glass fibre such as low price, low environmental impact and low embodied energy, have emerged as an alternative to the glass fibre in polymer composite. Fibre bearing plants release oxygen to the atmosphere and absorb carbon dioxide in contrast to the glass fibre, which therefore has a relatively high carbon footprint. For example, carbon footprint of one tonne of natural fibres is approximately 0.5-0.7 tonnes of CO_2-eq, whereas it is 1.7 – 2.2 tonnes CO_2-eq per one tonne of glass fibres [3]. Plant-based natural fibres can be classified as seed, bast and leaf fibres according to the locations of their availability in plants [4]. Those come from the stem of plants are known as bast fibres. Jute, flax, hemp, kenaf and rammie are the common bast fibres grown and processed for different textile applications. Jute is the most grown bast fibre in the world and considered as the second most important natural fibre after cotton [5]. Jute is cultivated and processed as fibre at large scale in Bangladesh, India and China mainly during the monsoon season, as it is a rain fed crop and grows in standing water. Two species of jute plants are commonly cultivated, they are *Corchorus capsularis* (white jute) and *Corchorus olitorius* (tossa or dark jute) [6, 7]. 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%) [8]. However, its chemical composition is specially characterised by the presence of Hemicellulose (13.6-20.4%) and exceptionally high content of lignin (12-13%). Therefore, jute is also identified as a lignocellulosic fibre. Although tensile strength of the jute fibre is lower than that of glass fibre, their density is approximately the half, therefore the specific modulus is higher, and tensile modulus is roughly similar to the glass fibre [5, 8]. From the sustainability point of view, jute production through plantation can bring a number of environment benefits. One hectare of jute plants consumes about 15 metric tonnes of CO_2 and liberates 11 metric tonnes of O_2 in only 120 days [9]. Greenhouse gas (GHG) emission from cultivation, harvesting and processing of jute fibre is lower than that of flax and hemp fibres [3]. Jute is a naturally adapted and well-resistant plant; usually use of any chemical fertilizer and pesticide is also very low in comparison to flax and hemp cultivation, and most of the times no such chemicals are required at all. Moreover, jute plants contributes around 5.43 million tons of dry leaves per year to the soil during defoliation process prior to retting in water. This leaves through natural decomposition enrich soil quality by an equivalent amount of fertilizer providing nutrients of 168,750 tonnes of Nitrogen and, 56,250 tonnes of Phosphorous and 150,000 tonnes of Potassium [9].

This is a tremendous contribution for the next crop (usually food grains rice or wheat) grown during immediate next dry season. Furthermore, jute sticks are used as structural material and an important biomass for clean energy production through burning in the rural areas.

1.2. Natural fibre reinforced composites (NFRC)

Natural fibre reinforced composite (NFRC) materials are gaining popularity for different applications in automotive, construction, sports and leisure, and consumer products, particularly where stiffness and low weight are more important than mechanical strength [5]. NFRC has 20-50% lower carbon footprint compared to GFRC [3]. Thermoplastic NFRC panels used in automotive components include wheel arch, bumper, engine shield, bonnet insulation, centre console trim, various damping and insulation parts, roof liner, C-pillar trim, rear parcel shelf, rear hatch, boot base, seat support, head rest, door trim panel and sub-floor covering etc. [10]. NFRC applications in construction include decking, railing, outdoor furniture, picnic table, garden benches, pallet, boards, NFRC rods, panels, tubes and I-beams; in sport and leisure sector, these include snowboards, canoe, surfboard, bike frames etc.; in consumer products, they include indoor furniture components, tableware, handles, electric goods, rigid packaging, plant pots and mobile phone components etc. [2, 5].

Jute reinforced composite has potential applications in window and doorframes, indoor furniture panels, automotive panels and upholstery, parcel shelves and noise insulating panels etc. [12]. An example of the application jute-based thermoplastic composite is the automotive door panels produced and commercialised by German automaker Mercedes-Benz in the 90s [7, 12]. A very interesting finding by Monetrio et al. [11] shows that use of jute fabrics reinforced polyester composites (see Table 1) an inner layer between ceramic and aluminium alloy in a multi-layered armour system (MAS) exhibited similar ballistic performance to that of much stronger Kevlar (an aramid fabric) laminate. This opens up the application of jute composite in the construction of military vehicle and protective warfare structures.

1.3. Comparative analysis of contemporary research works on jute fabric reinforced composites

Textile materials are available in different forms, such as short fibre, long fibre, sliver (a untwisted linier structure of fibres before converting into yarn), yarn, woven and knitted fabrics and nonwoven sheet [4]. In contemporary research works, jute has been utilised in all the forms of fibre [13, 14], sliver [15], yarn [16, 17], woven fabric [18, 19], knitted fabric [19] and non-woven sheets [20, 21] to fabricate jute reinforced composite materials, using either thermoplastic [21] or thermoset polymeric matrices [13, 15, 17]. However, a very limited number of works focused on jute fabric reinforced layered composite materials (see Table 1). Hydaruzzaman et al. [22] treated bleached fabric of tossa jute (Corchorus olitorius) 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. [23] 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. [24] prepared composite by compression moulding of four layers of hessian fabrics within five layers of PVC and found the composite containing 40 wt% fibre showed the best performance. An increase in tensile, flexural and interlaminar shearing strength was observed by Seki et al. [25] in composite made from alkali and oligomer siloxane treated single layer of jute fabric compression moulded into two layers of high-density polyethylene (HDPE). Zaman et al. [26] 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 moulding. They found best results from 70% oligomer treated fabrics. Berhanu [27] 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 [18] reported a jute-vinylester composite material by compression molding of four layers of alkali treated jute fabrics (16 Ends per Inch (EPI) & 13 Picks per Inch (PPI); 430 gram per square meter (GSM)) impregnated with a solution of vinylester resin, catalyst and accelerator. Arju et al. [19] 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. Khan et al. [28] discussed an ecofriendly bio-composite made by compression molding of single layer of jute fabrics sandwiched between poly (L-lactic acid) (PLLA) films. El Messiry and El Deeb [29] prepared single layers composite laminate from jute fabric pultruded with different combination of resin/solvent ratios. They found that mechanical properties of composite can be engineered with the variation of resin/solvent blend ratio without changing fibre volume fraction. It should be noted that quality and performance of jute-based substance may significantly vary between the species (i.e. tossa and white), raw fabric condition (i.e., bleached and unbleached) and fabric construction (i.e., weave design and yarn density). As it can be seen in Table 1 that the reproducibility of these works is very much limited as all of them except Khan et al, [24] did not mention any of the vital information about fibre type, fabric structure and raw fabric condition. Therefore, it is challenging to compare the results of various studies available in the literature.

Table 1: Contemporary research on jute fabric reinforced composite fabrication

Jute Fabric				Pre-treatment	Matrix	Number of Jute Fabric Layer	Composite Type	Method	Reference
Fibre Type	**Fabric Design**	**Fabric Structure**	**Raw Fabric Quality**						
Tossa	Likely woven*	*nm*	Bleached	Monomer Methyl-methacrylate (MMA)	Urethane acrylate Oligomer + 2% photo-initiator in methanol	5	Thermoset	UV curing + Heat press	[22]
nm	Woven	*nm*	Unbleached	Atmospheric plasma (He/ Ac/N)	Polyester Resin	12	Thermoset	Vacuum bagging + curing	[23]
nm	Woven	Hessian (plain weave)	Bleached	Hexanedioldiacrylate (HDDA)	Urethane acrylate oiligomer	5	Thermoset	UV curing + Heat press	[26]
nm	Woven	plain weave	*nm*	Alkali	Vinylester resin, catalyst and accelerator	4	Thermoset	Compression moulding + Curing	[18]
Tossa	Likely woven*	*nm*	Bleached	2-hydroxyethyl methacrylate (HEMA) and starch	Polypropylene	4	Thermoplastic	Heat press	[30]
Tossa	Woven	Hessian (plain weave)	Unbleached	n/a	Polyvinyl chloride (PVC)	4	Thermoplastic	Heat press	[24]
nm	*nm*	*nm*	*nm*	Alkali and oligomer Siloxane	High-density polyethylene (HDPE)	1	Thermoplastic	Heat Press	[25]
nm	Woven	nm	*nm*	n/a	Polypropylene	2	Thermoplastic	Heat press	[27]
nm	Woven	Plain weave (52x44)	*nm*	n/a	Poly (L-lactic acid) (PLLA)	1	Thermoplastic	Heat press	[28]
nm	Woven and knitted	Plain, twill, single jersey and rib	*nm*	n/a	Polypropylene (PP)	1	Thermoplastic	Heat Press	[19]
nm	Woven	Plain	*nm*	n/a	Bisphenol A epoxy +	1	Thermoset	Pultrusion	[29]

					Polyamide Triethylene Tetramine				
nm	Woven	Plain	*nm*	n/a	Orthophthalic polyester esin + 1wt% ethyle mythyle ketone	3,6,9	Thermoset	Curing + Heat Press	[11]
Note: *although not mentioned, it appeared to be woven fabric from discussion; nm = not mentioned; n/a = not applicable									

1.4. Statement of research gap, research rationale and aim of this paper

Current literature shows that no work was previously carried out on developing multilayer laminate with jute fabrics and High-Density Polyethylene (HDPE). However, it offers economic advantages due to lower price than polypropylene. As HDPE is mechanically less strong than the commonly used other polymers such as polypropylene, any improvement of HDPE by reinforcing with natural fibres will 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.

2. MATERIALS AND EXPERIMENTAL METHOD

2.1. Raw Materials

Fig. 1 presents a general flowchart of jute fabric manufacturing. A 100% hessian fabric (Fig. 1d) made of tossa jute collected from Janata Jute Mills Ltd. in Bangladesh was used as a filler material for manufacturing laminated polymer composites. The specification of the jute fabric has been evaluated through visual inspection and relevant tests presented in Table 2. Structure of the jute fabric (number of yarns in 100 mm) and weight (GSM) were determined following the standards BS EN 1049-2:1994 [31] and BS 2471:2005 [32] respectively. The breaking force and elongation of the fabric (3 specimens in warp and 3 specimens in weft direction having 50 mm width in each case) were analysed following the test standard BS ENISO 13934-1:1999 [33] and using "Testometric Micro 500" (UK) testing machine. Fibre orientation within the jute fabric was investigated using an optical microscope. HDPE sheets with a thickness of 1 mm were purchased from Direct Plastics Ltd, Sheffield, UK and the general specification of the sheet is given in Table 3.

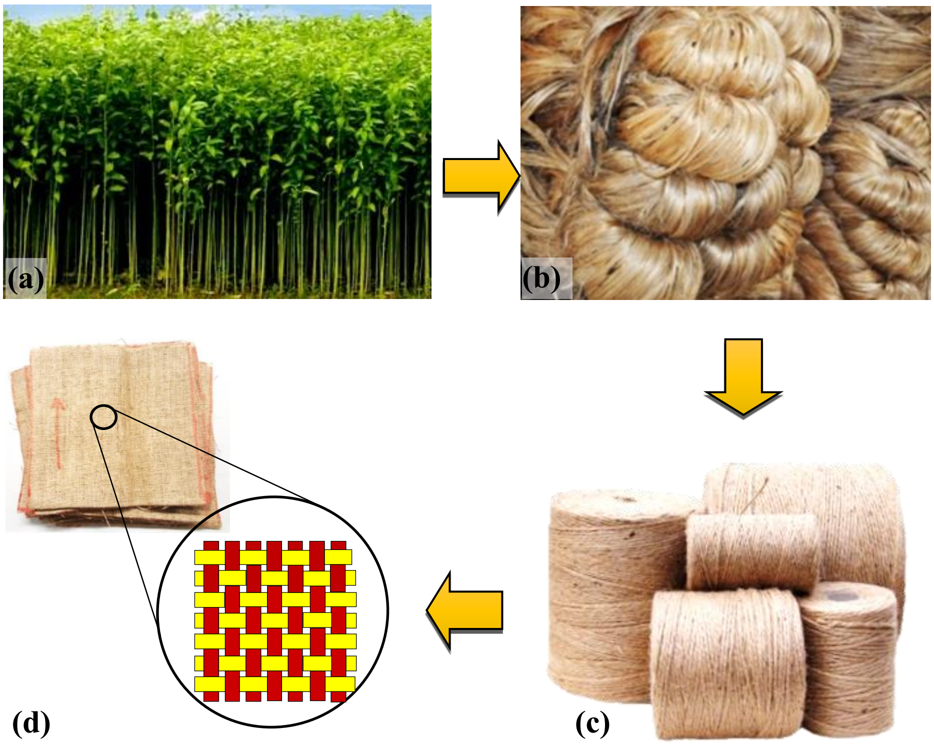

Fig. 1: (a) Jute plant, (b) Jute fibre after retting and drying, (c) Jute yarns after spinning, (d) Jute fabric – Hessian structure (inset plain weave design) used in this research

Table 2. Specification of jute fabrics

Parameters	Value	Unit	Test standards
Weave design	1/1 (plain)	-	BS EN 1049-2:1994
Warp	39	Ends per 100 mm	
Weft	35	Picks per 100 mm	
Weight	209	g/m^2 (GSM)	BS 2471:2005

Table 3. Specification of HDPE sheet [34]

Parameters	Value	Unit
Colour	Natural	-
Density	0.947	g/cm^3
Tensile Strength at yield	25	MPa
Hardness	64	Shore D
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 [35] 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 laminate of pure HDPE. Fig. 2 shows the layup sequence of multilayer jute fabrics stacked at 0° orientation along the warp (i.e. lengthwise) direction between a total seven layers of HDPE sheets in order to maintain a constant thickness in all composites. 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. For 6-layer design, fabrics and HDPE sheets are placed alternately having HDPE at the both outer ends.

Dry jute fabrics taken out from the oven were first weighed, immediately stacked in between the HDPE layers according to the designs by hand lay-up technique (see Fig. 2) 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 jute fabrics were carefully stacked with the same orientation. Furthermore, the stacked materials in the die were placed between two steel plates and compression moulded in a hot press (Bradley & Turton Ltd., Kidderminster, UK) as shown in Fig. 3(a) at 195°C for 20 min under a pressure of 12.4 MPa. Heat resistant Teflon sheets were placed between the staked structure and steel plates for easy release after hot pressing. Then the composite laminate with the die was cooled to room temperature using another water-cooled press under a pressure of 3.10 MPa for 10 mins (Francis Shaw & Co., Manchester, UK). Finally, the laminate was taken out from the die (Fig. 3b), weighed for weight fraction calculation and cut in warp direction by a vertical bandsaw machine for preparing specimen for mechanical testing. The specimens were deburred and polished in a grinding machine to remove any stress rising points. Pure HDPE laminate of same dimensions was also prepared following the same procedure for the purpose of comparison. Jute fabric weight fraction in the laminates were calculated from difference between the laminate and fabric weights using the following formula (Eq. 1) [28].

$$W_f = \frac{w_j}{w_p + w_j} \qquad (1)$$

Where W_f, w_j, and w_p are the weight fractions of jute fabric in the polymer composite, weight of jute fabric and weight of HDPE polymer matrix respectively. 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 (wt% means weight percentage).

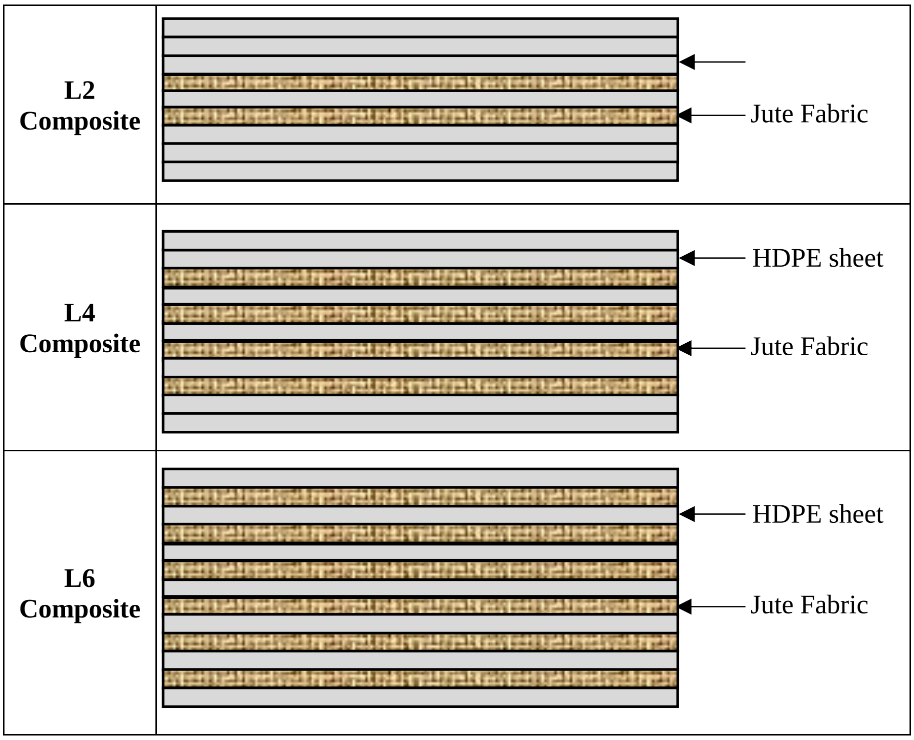

Fig. 2. Schematic diagrams of the layup sequence of multi-layered HDPE-jute composites

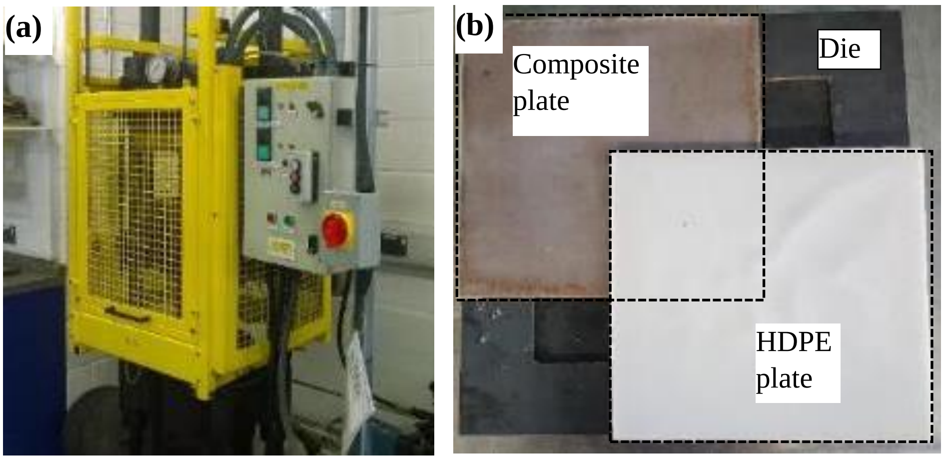

Fig. 3. (a) Hot press for compression moulding (b) prepared composite and HDPE plates with die

2.3. Mechanical Testing

Tensile tests of HDPE-jute and HDPE only specimens were carried out on Hounsfield H10 KS Tensometer, UK testing machine equipped with a 10,000 N load cell, according to ASTM D-3039 [36]. The cross-head speed used for the tensile specimens was 50 mm/min. System control and data analysis were performed using Qmat 5 software system. Specimens with a nominal dimension of 177 mm × 20 mm × 6.5 mm (length × width × thickness) for each type of composite laminates were tested. However, the dimensions of individual test samples were measured during every test 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 resulting in higher resistance to crack propagation [28, 37]. Tensile stress (σ) and strain (ε) were calculated from the test data using Eq. 2 and Eq. 3.

$$\sigma = \frac{F}{bd} \tag{2}$$

$$\epsilon = \frac{\Delta L}{L_o} \tag{3}$$

where *F* is the applied tensile load (N), *b* is the specimen width (mm), *d* is the specimen thickness (mm), L_o is the specimen length (mm) and ΔL is amount of extension. Young's modulus was calculated from the initial slope of the stress-strain curve using Eq. 4.

$$E = \frac{\sigma}{\epsilon} \tag{4}$$

The flexural strength and tangent modulus of elasticity of the HDPE-jute composites and HDPE plate were measured using a three-point bending test according to ASTM D790-02 [38] 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 flexural strength (σ_f) and modulus (E_f) were calculated using Eq. 5 and Eq. 6 respectively.

$$\sigma_f = \frac{3F_f L}{2bd^2} \tag{5}$$

$$E_f = \frac{mL^3}{4bd^3} \tag{6}$$

where F_f is the applied flexural load (N), *L* is the span length (mm) and *m* is the slope of the initial straight-line portion of the load-deflection curve. The number of samples tested for each type of specimen ranges between three to four. Fig. 4 presents the tensile and flexural test set-ups.

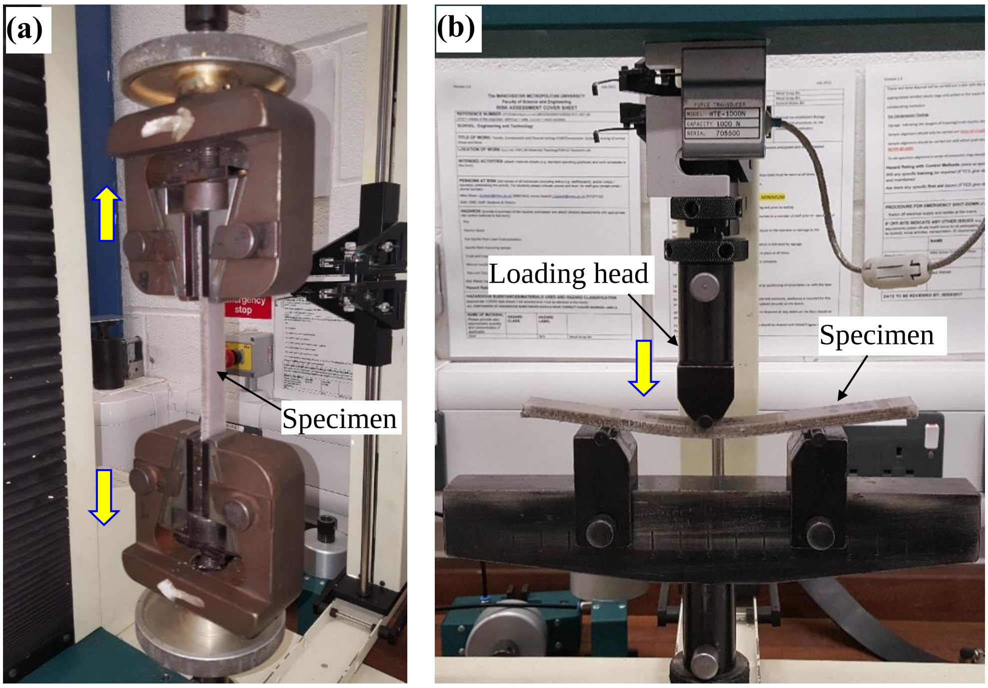

Fig. 4. Experimental arrangements for (a) Tensile and (b) Flexural tests

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 composites. The cut and fracture surfaces of the HDPE-jute composites were also observed under a scanning electron microscope (SEM) to analyse adhesion and interfacial characteristics between the jute fabric and HDPE matrix. An SEM of model JSM-5600LV from JEOL Ltd. was used at an accelerating voltage equal to 20 kV in secondary electron mode.

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. 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. 5). Some degree of non-uniformity in the diameter of the yarn and gap between the yarns were also observed. It is clear from the breaking force test results presented in Table 4 that average breaking force is approximately 31% higher in the warp direction compared to the strength in the weft direction. The results agree with the values mentioned in the literature [39]. On the other hand, average breaking extension exceeds by 13 mm in the warp direction. Therefore, the tensile strength tests of the composites were confined to mainly in the warp direction. Even though jute fibre has high strength, its failure mode was observed as brittle fracture [39]. Furthermore, the fibres broke only by small extension ranging from 5.9-6.7% indicating low elastic property.

Table 4. Tensile properties of jute fabric

Parameters	Value	Unit	Test Standard
Average Breaking Force (Warp)	432.9 ± 72.52	Newton	BS EN ISO 13934-1:1999 [33]
Average Breaking Force (Weft)	330.9 ± 15.21	Newton	
Average Breaking Extension (Warp)	13.31 ± 2.59	mm	
Average Breaking Extension (Weft)	11.81 ± 1.83	mm	
%Average Breaking Extension (Warp)	6.7 ± 1.29	%	
%Average Breaking Extension (Weft)	5.9 ± 0.91	%	

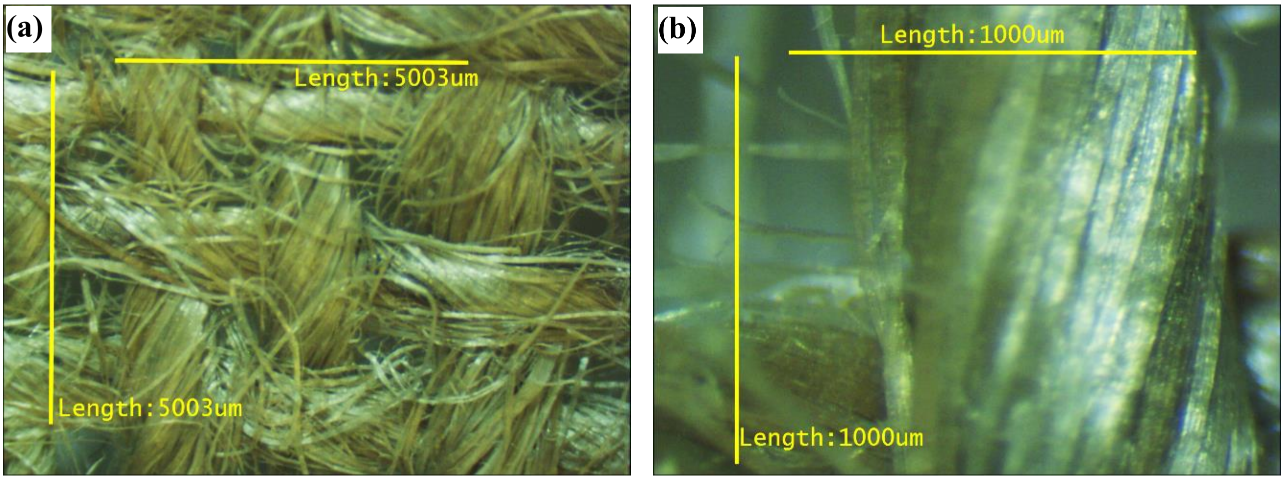

Fig. 5. Magnified views of (a) jute fabric and (b) jute fibres

3.2. Physical Characteristics of Composite

Fig. 6 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.

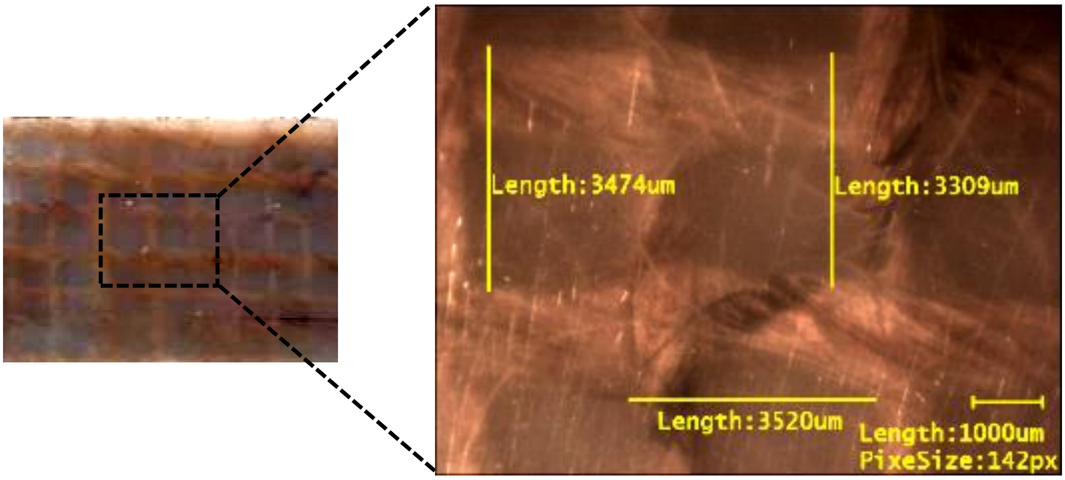

Fig. 6. Top surface views of HDPE-jute composite under an optical microscope

The polished cross-sectional view of the specimen revealed that the layers of the jute fabrics were also evenly spaced in the HDPE matrix even after high compression moulding process (Fig. 7a). This ensured complete wetting between the layers by the matrix material in order to reduce the chances of interfacial adhesive failure might occur particularly under tensile loading condition. No visible voids were present in the matrix or at the interface between yarn and matrix across the thickness of the samples even at high magnification and the layers were completely immersed within the matrix, which are an indication of good quality composite. The magnified view of a yarn (Fig. 7b) 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, further higher magnified view revealed that even at this higher pressure the melt polymer could not wet all fibres uniformly in the yarn, which left some degree of voids between the fibres as shown in Fig. 8. These voids could act as sites for crack propagation under the application of load on the composites.

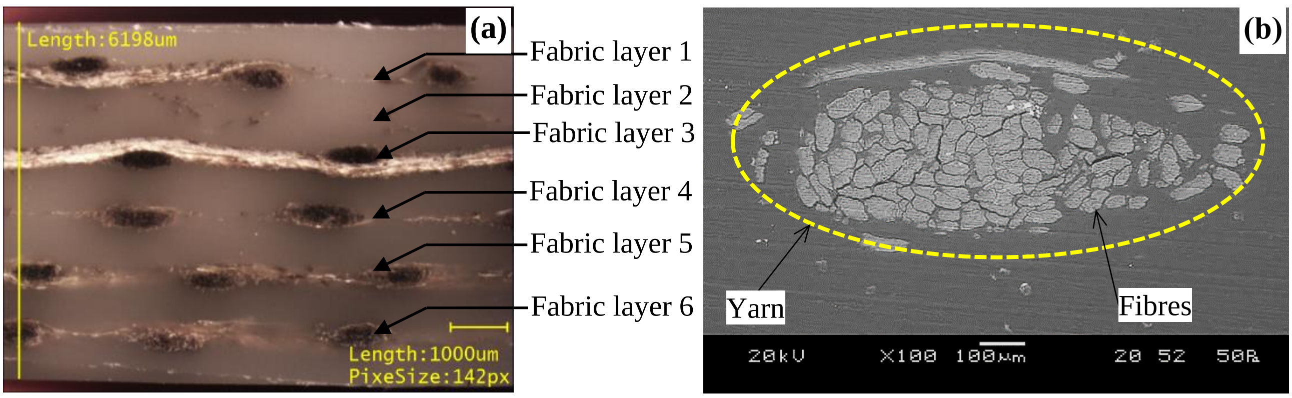

Fig. 7. Cross-sectional view of jute-HDPE composite: (a) individual fabric layers in the matrix under an optical microscope and (b) a yarn with fibres under an SEM

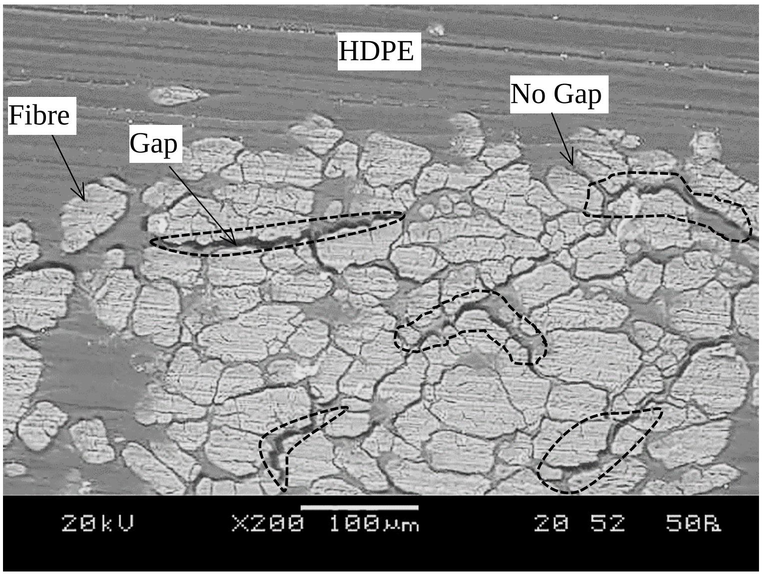

Fig. 8. Cross-sectional view of jute yarn in HDPE matrix showing gaps between fibres and matrix

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 clear separation between the jute layers by HDPE material. Initial tests showed that beyond six layers within the given die thickness, it was difficult to maintain the jute layer separation within the matrix. The separation jute layers within the matrix could create strong interfacial bonding through matrix fibre interpenetration and mechanical interlocking [39], which could be a critical factor for the mechanical performance of the composites particularly under tensile loading condition. Furthermore, with more than 6 jute layers in the composite an uncontrolled relative movement distorted the layered structure leading to an inconsistent and poor quality of layered composite. 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 possibly due to the same reason.

3.3. Mechanical Properties of Composite

Table 5 presents the results from the mechanical tests and corresponding improvements. They will be discussed in the following sub-sections.

Table 5. Results from the mechanical tests and corresponding relative improvements in the composites with respect to the pure polymer material

Specimens	**Tensile strength (MPa)**	**Improvement in tensile strength (%)**	**Young's Modulus (GPa)**	**Improvement in Young's Modulus (%)**	**Flexural strength (MPa)**	**Improvement in Flexural strength (%)**	**Flexural Modulus (GPa)**	**Improvement in Flexural Modulus (%)**
HDPE	22.39	-	1.538	-	24.84	-	1164.67	-

L2 composites	26.64	19.01	1.591	3.48	24.64	-	1177.50	1.10
L4 composites	26.71	19.30	2.141	39.20	29.21	17.58	1499.00	28.71
L6 composites	36.37	62.47	2.659	72.93	38.73	55.88	2503.67	114.97

3.3.1. Tensile Strength Tests

Fig. 9 presents typical tensile stress-strain curves for pure HDPE and jute fabric reinforced layered composites. There was a clear pattern of step change in slopes of the curves for the composites indicating a transition from linear (initial portion of the curves) to non-linear material behaviour before the maximum load as a result of initial crack development within the matrix followed by progressive fibre pull-out or fibre failure [28, 37]. As the fibre content was increased in the composites, the tensile strength increased. This could be explained by the fact that woven jute fabrics in the HDPE matrix increased load carrying capacity of the composites [40]. However, not much difference in the strengths between L2 and L4 composites was noticed. This could be due to structural distortion of the fabric or non-uniform arrangement within the composite thickness. The failure of the composites with increasing fibre content in comparison to the pure HDPE can be characterised as ductile to progressively brittle with lower strain rate. This behavior is also demonstrated in Fig. 10, where the extensions at peak forces are gradually decreasing with the increase of the jute fibre content in the composites.

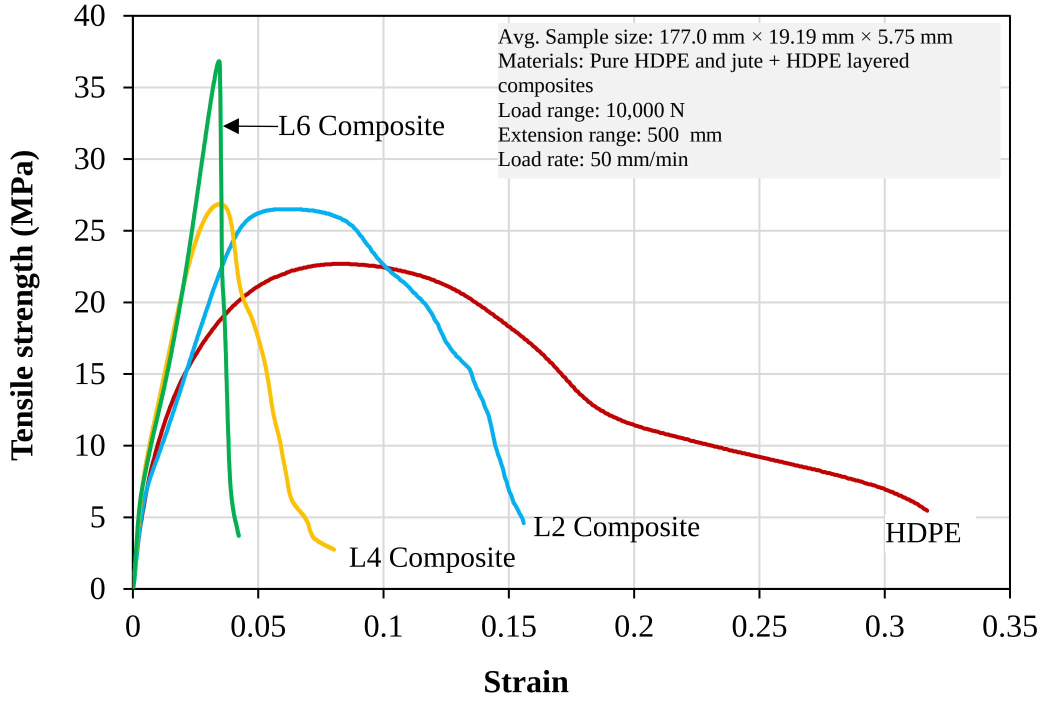

Fig. 9. Tensile stress-strain curves for HDPE and different HDPE-jute composites

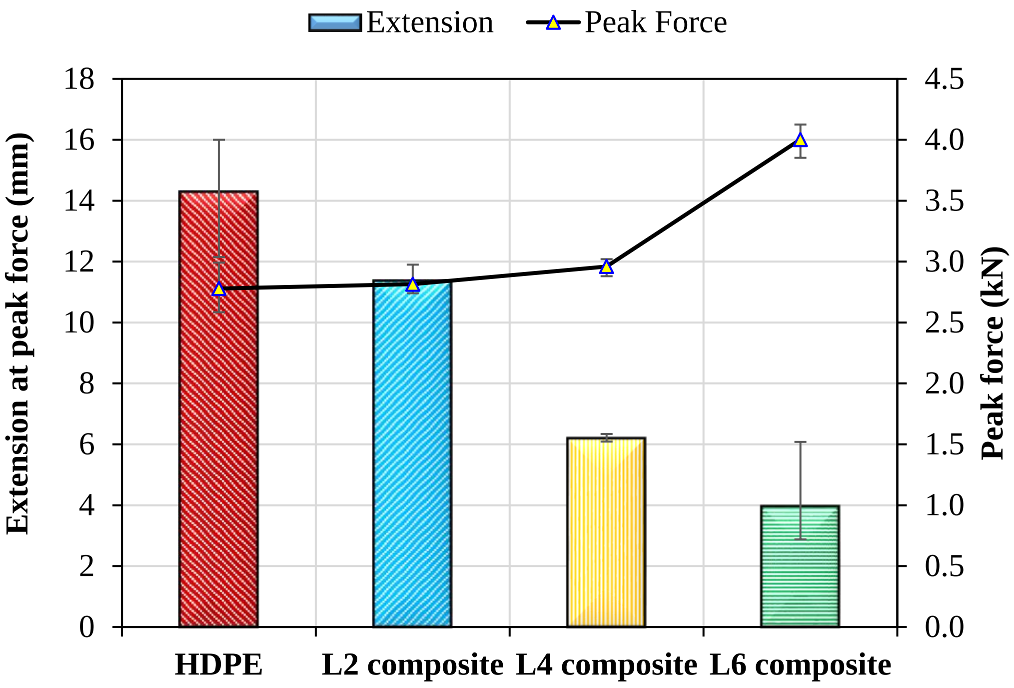

Fig. 10. Extensions at peak forces for HDPE and HDPE-jute composites during tensile testing

In fibre reinforced polymer matrix, the tensile strength is dependent on the interfacial bonding between the matrix and the fibres. Therefore, a strong interface, minimum stress concentration, and appropriate fibre orientation are essential to obtain the required strength. On the other hand, stiffness defined by the Young's modulus can be obtained with favourable fibre characteristics such as high fibre aspect ratio, higher fibre concentration, and better fibre wetting in the matrix [41]. Fig. 11 and Fig. 12 present the tensile properties of pure HDPE and the composite materials. The results clearly indicated that in general all layered composites possessed higher tensile strengths than the pure HDPE sample.

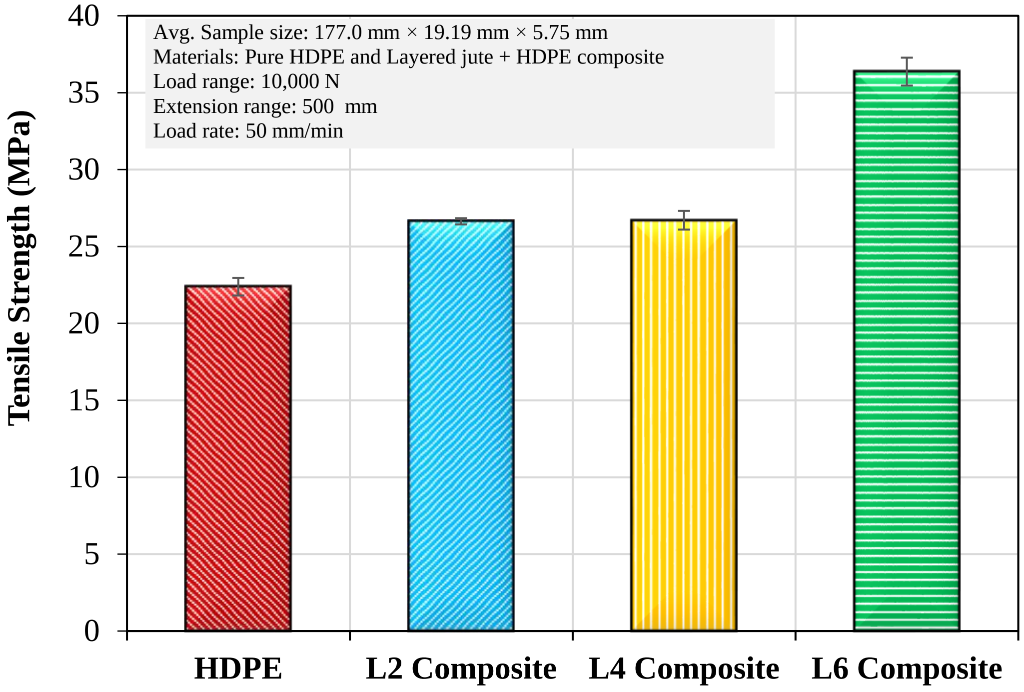

Fig. 11. Tensile strength of pure HDPE and layered HDPE-jute composites in warp direction

The tensile strength of the HDPE laminate with similar dimension of HDPE-jute 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 HDPE-jute (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. [19] and Seki et al. [25]. A maximum strength improvement by approximately 62% was achieved with the composite containing six layers of jute fabrics (L6 composite). A tensile strength improvement of 19% was realised with 2-layer composite. An improvement Young's modulus by approximately 39% and 73% were achieved with the composite containing four layers (L4 composite) and 6 layers of jute fabrics (L6 composite). In addition, no significant improvement in Young's modulus was seen in L2 composite from pure HDPE laminate. This could be due to several reasons such as non-uniform jute layer distribution in the matrix and uneven yarn density in fabric structures, which is quite common as the hessian fabric primarily made for low end bag and sacking application, where strict quality control process is not followed to keep the price as low as possible. Furthermore, a minimum critical weight fraction of jute is required to realise obvious improvement in the composite stiffness. In this case, it seemed that four jute fabric layers or 12.90wt% would be the critical fibre weight fraction in the composite.

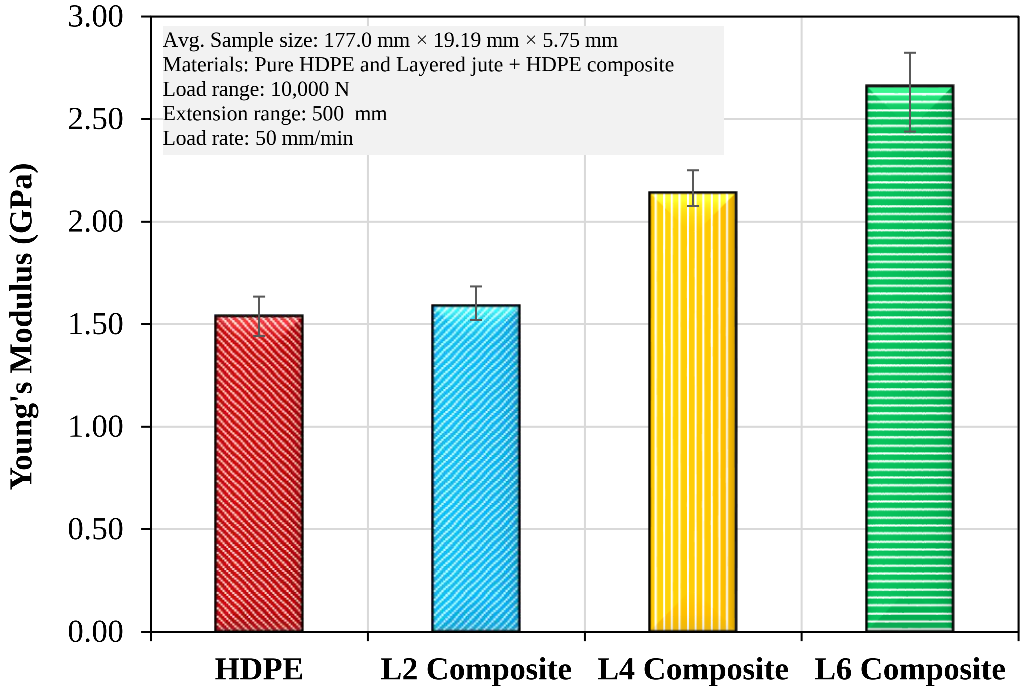

Fig. 12. Comparison of Young's moduli of pure HDPE and layered HDPE-jute composites

Arju et al. [19] 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. [25] 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 of jute fibre without specifying the details of the fabric structure used. After treating jute fabric with oligomeric siloxane solution, the tensile strength of the HDPE-jute composite could be improved up to 29.1 MPa and the modulus up to 1.47 GPa due to the increased adhesion between jute fiber and HDPE matrix. The findings from the current work show that layered jute fabrics within HDPE matrix can provide higher tensile strength (36.37 MPa) and young's modulus (3.60 GPa) without any chemical treatment on jute fabrics. It should be noted that the results cannot be directly compared with the literature even though the matrix and fibre content are similar as the composite construction and fabric processing/treatment are different.

3.3.2. Flexural Strength Tests

Flexural stress-strain curves for different layered composites with varying weight percentages of jute fibre is presented in Fig. 13. In general, all the specimens showed a nonlinear stress-strain behavior typical of layered composite material. The crack started to form on the outer side of the sample subjected to tensile stress and slowly propagates across the sample thickness. It is very clear from the figure that flexural strengths of the composites are higher than that of pure HDPE and with the increase of fiber weight content, the flexural strength increases as indicated by the rising change in slope of the curves. At the peak compressive loading, no breaking of the composite samples was observed. Flexural properties of HDPE laminate and HDPE-jute composites are compared in Fig. 14 and Fig. 15. Average flexural strength and modulus of pure HDPE laminate were tested as 24.84 MPa and 1.165 GPa respectively, whereas the values of 4-layer HDPE-jute composite were found as 29.21 MPa and 1.49 GPA respectively. This means that an increase in flexural strength and modulus by 17.58% and 28.71% respectively is achieved with 4-layer composite when compared to the pure HDPE laminate. Further increase in flexural strength and modulus by 55.88% and 114.97% respectively were found in 6-layer HDPE-jute composite in comparison to the pure HDPE laminate. Seki et al. [25] 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 HDPE-jute 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 composites and pure HDPE. This could indicate that in order to achieve a noticeable improvement of flexural strength with a force applied in the lateral direction, a minimum critical weight fraction of jute is essential. On the other hand, a small weight percentage jute can make noticeable improvement in the tensile properties under a force in the longitudinal direction.

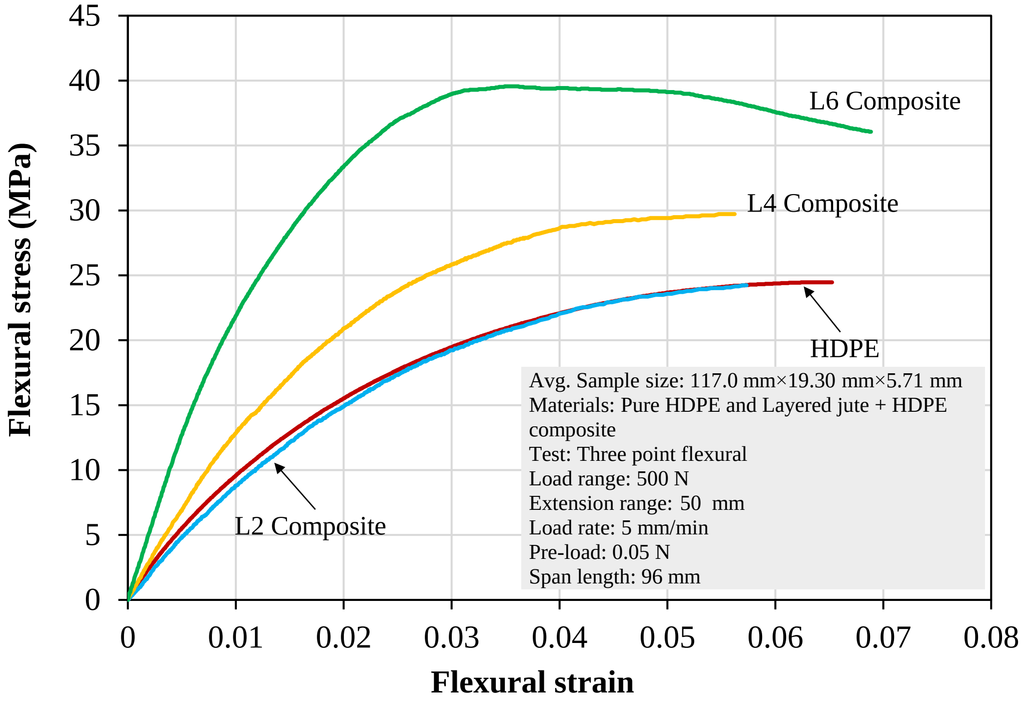

Fig. 13. Flexural stress-strain curves for HDPE and different HDPE-jute composites

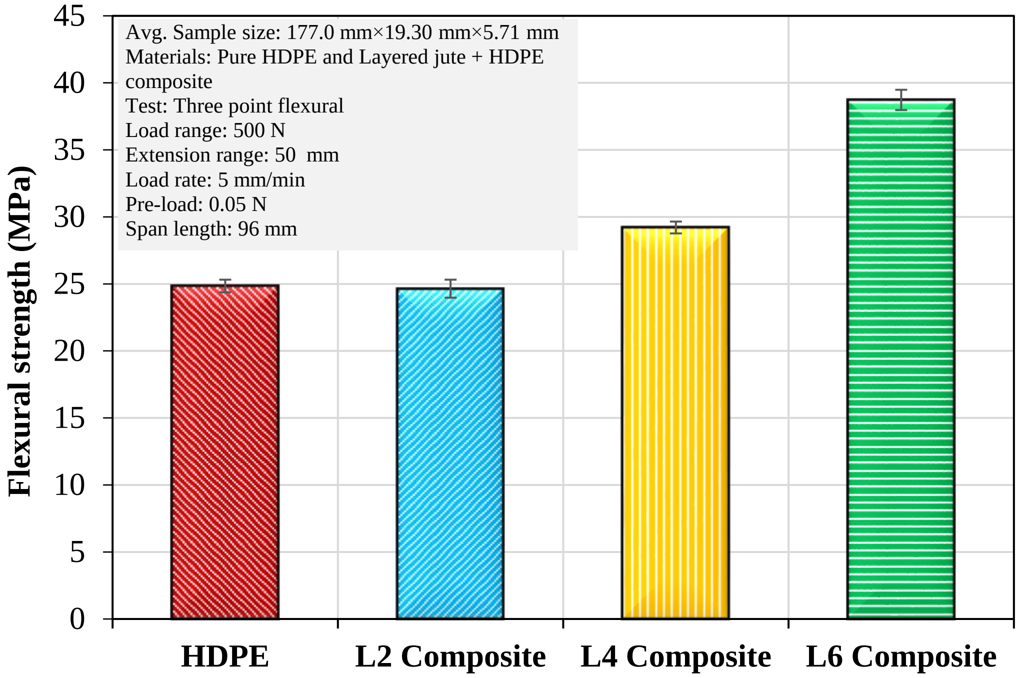

Fig. 14. Comparison of flexural strength of pure HDPE and layered HDPE-jute composites

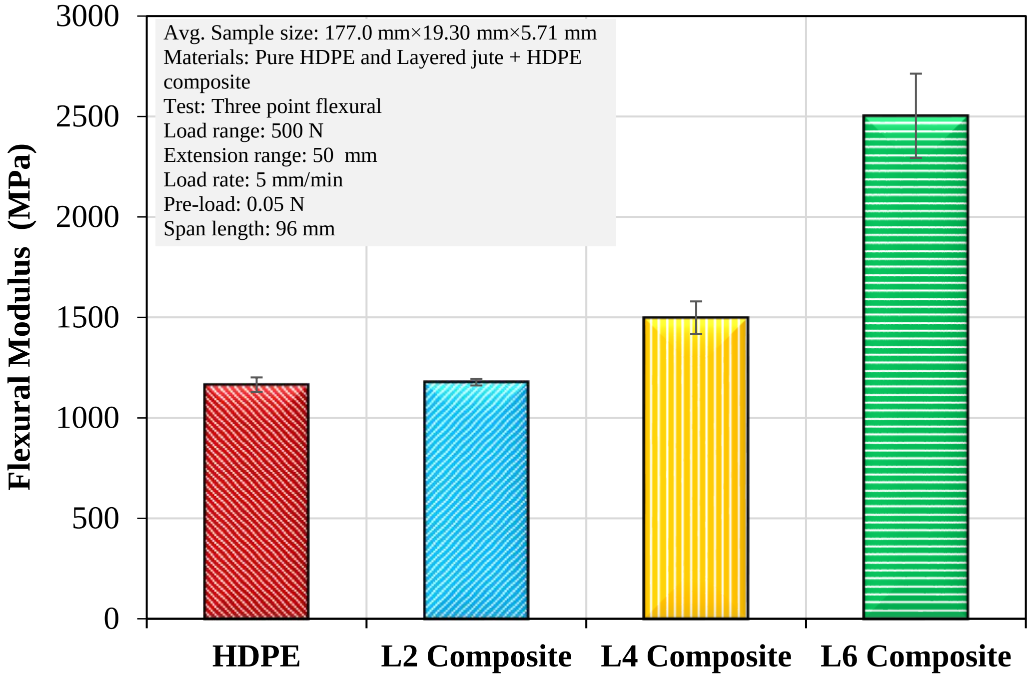

Fig. 15. Comparison of flexural moduli of pure HDPE and layered HDPE-jute composites

3.4. Interfacial Surface Morphology

In general, three parameters are responsible for the performance and properties of fiber reinforced polymer composites: properties of fibre, properties of matrix and the interfacial characteristics between the matrix and the fiber. Good interfacial adhesion through chemical and mechanical interlocking between the matrix and the fiber with high degree of fibre wetting is the determining factor to achieve improved strength in the composite [39]. This has been explained by the fact that higher bonding strength has the ability to transfer the stress from the matrix to the fibre [42]. The magnified views of the cut surfaces (Fig. 16a) showed no void or air gap across the thickness of the composite laminates with good wetting of the yarns. HDPE material was well bonded with the yarn of the jute fabric. On a macroscopic level, the good bonding at the interface between jute yarn and HDPE matrix could be the major contributing factor for improved tensile and flexural strengths found in the composites. However, there was little evidence of HDPE polymer around the fibres within the yarn (Fig. 16b). This indicated that the polymer matrix could not reach inside the yarn fully even at high pressure and temperature during compression moulding.

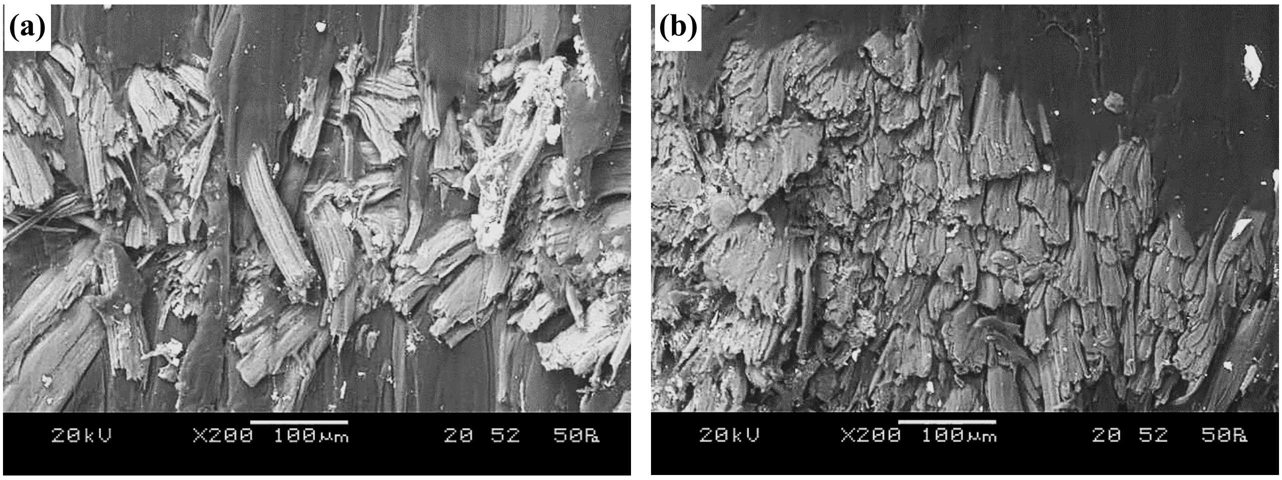

Fig. 16. SEM pictures of cut surfaces from HDPE-jute composite

Under tensile loading condition, the composite material started failing from the interface, followed by extensive fibre pull-out from the matrix and finally tearing of the fibres in individual yarns as evidenced in Fig. 17(a). 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 within the yarns owing to lack of fibre wetting similar to what was observed in [43]. Relatively clean fibre surfaces also indicated extensive interfacial failure under tensile force owing to the poor fibre/matrix adhesion (Fig. 17(b)). At high magnification, a clear gap could be seen in some places between the matrix and a yarn. However, there were also strong evidences of polymer material adhering with the outer fibres of a yarn in tensile fractured surfaces (Fig. 17c,d). In summary, it can be said that even without any fabric treatment enough bonding at the fibre matrix interface helped to share part of the stress by the fibres and contributed to the improvement in mechanical properties of the composite.

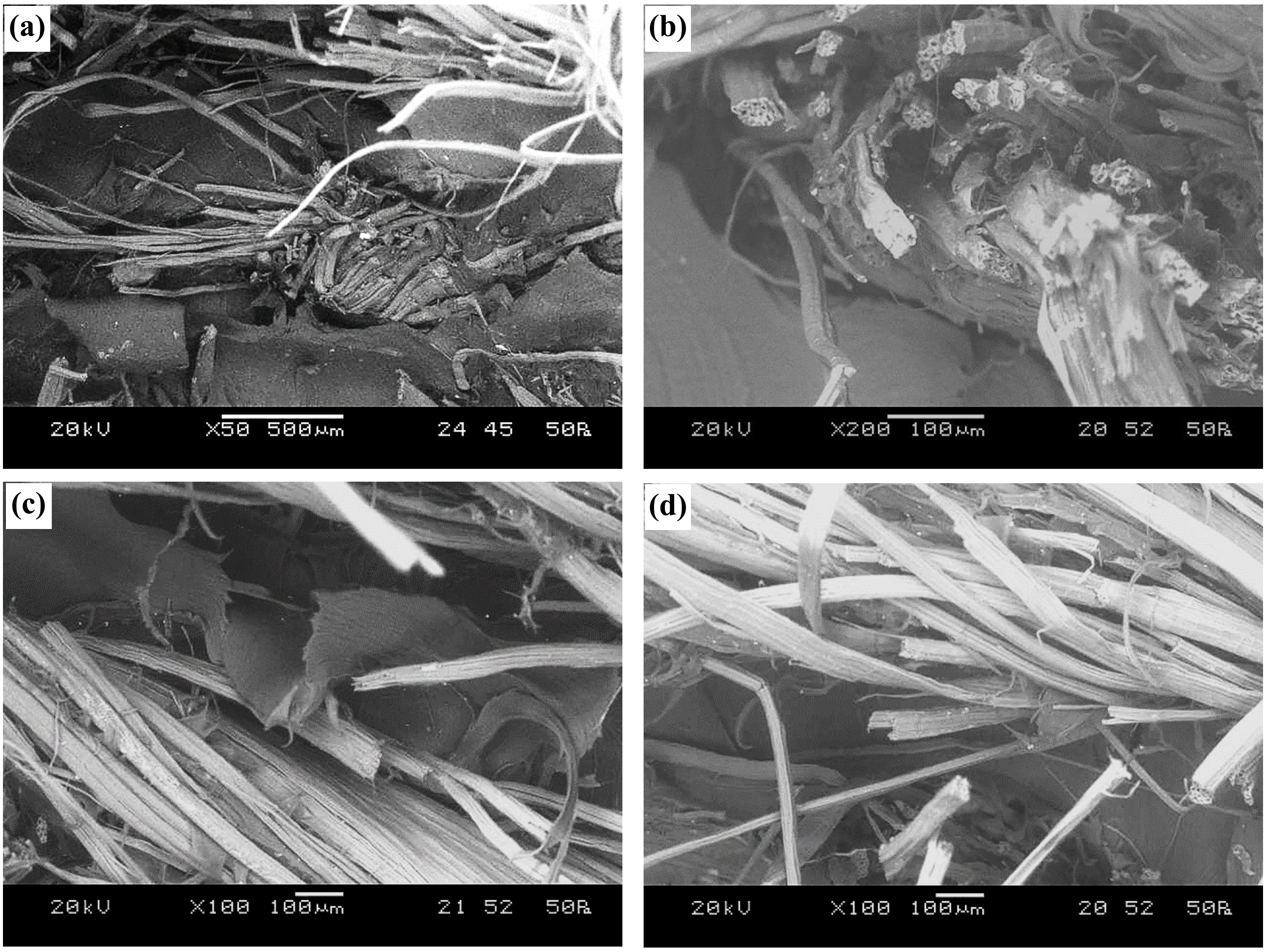

Fig. 17. SEM pictures of tensile fractured surfaces from HDPE-jute composite

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 die thickness of approximately 6.5 mm. 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 content of jute fabric (in wt%) 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 at the fibre matrix interface were observed in the fractured specimens under tensile loading condition possibly due to inadequate interfacial adhesion.

The notable finding from this study is the achievement of higher mechanical properties in multilayered HDPE-jute composite without any chemical treatment of jute fabrics. Any additional treatment negates the sustainability advantages of natural fibres by increasing carbon footprint and cost. This will also decrease the competitive advantage of jute against glass fibre. This work primarily focused on identifying the optimum number of jute fabric layers for given width of composite laminate. In future, those additional physical, mechanical and thermal properties of the composites will be investigated and use of different thermoplastic matrices will be studied for comparative analysis.

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