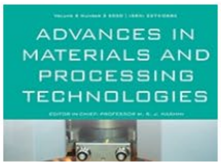

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Thermoplastic Composites reinforced with Multi-layer Woven Jute Fabric: A Comparative Analysis

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Abstract

Three commonly available thermoplastic matrices - High-density polyethylene (HDPE), polypropylene (PP) and nylon 6 – are reinforced with hessian jute fabric in multi-layer sequence to prepare composite laminates by compression moulding technique. The composite had a nominal fibre content of 18% in terms of weight and a nominal thickness of 6.5 mm. The mechanical and fracture behaviours of the resultant laminates are tested and compared. It was found that the Nylon-Jute composite exhibited the highest values of tensile strength, Young's modulus, flexural strength, flexural modulus and hardness. On the other hand, HDPE-Jute composite showed relatively poor performance. Interestingly, the HDPE-Jute composite exhibited the highest impact strength and the Nylon-Jute composite was the poorest in this regard. The amount of water absorption by the composites from highest to the lowest was found in the following order: Nylon-Jute > HDPE-Jute > PP-Jute.

Keywords

Natural fibre; jute; woven fabric; high-density polyethylene (HDPE), polypropylene; nylon; composite; laminate

1. Introduction

The use of bast fibres, for example, jute, flax, hemp and kenaf, as a filler in different composite structures has challenged the monopoly of glass fibre reinforced composite (GFRC) materials on sustainability ground in the application areas, where stiffness and low weight are more important than the mechanical strength [1–6]. The carbon footprint of one Kg of glass fibre is 1.7–2.2 Kg CO_2-eq, whereas for any natural fibre (per one Kg) it is as low as approximately 0.5–0.7 Kgof CO_2-eq. [3]. Natural fibre reinforced composites (NFRCs) exhibit 20%–50% lower carbon footprint compared to the GFRC. Therefore, the application of NFRCs in automotive, construction, sports and leisure, and consumer products has started to gain significant momentum [5–8]. Automotive components including 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, headrest, door trim panel and sub-floor covering, etc. can be made from NFRCs [6,8]. In construction sector, examples of the uses of NFRCs include decking, railing, outdoor furniture, picnic table, garden benches, pallet, boards, panels, tubes and I-beams, etc. NFRCs are also gaining popularity in making sport and leisure products such as snowboards, canoe, surfboard, bike frames, etc. Moreover, consumer products made of NFRCs include indoor furniture components, tableware, handles, components of electric goods, rigid packaging, plant pots and mobile phone components etc.

Among many natural fibres, jute, a lignocellulosic fibre, has attracted significant attention as an alternative to glass fibre as a filler in composite manufacturing due to its low price and the sustainability advantages it offers [9]. According to the Food and Agriculture Organization of the United Nations (FAO), growing one Mg of jute fibre requires less than 10% of the energy used for the production of one Mg of synthetic fibres and the jute plant absorbs as much as 2.4 Mg of carbon per Mg of dry fibre [2]. Jute plants grown in one hectare of land consume about 15 Mg of CO_2 and liberate 11 Mg of O_2 in only 120 days before harvesting [10]. In comparison to the glass fibre, the jute fibre has lower density but higher specific modulus and nearly equivalent tensile modulus [11]. Potential applications of jute reinforced composite materials are identified as window and doorframes, indoor furniture panels, automotive panels and upholstery, parcel shelves and noise insulating panels etc. [4,12]. Recent work by Monetrio et al. [13] showed a potential use of jute fabric reinforced polyester composite as an inner layer between ceramic and aluminium alloy in a multi-layered armour system (MAS). Although the German automaker Mercedes-Benz demonstrated the use of jute-based thermoplastic composite in the automotive door panels more than thirty years ago [4], it failed to capture any significant market share due to week marketing initiative as well as lack of scientific research from the jute producing countries over the long period of time. However, a resurgent of scientific activities on jute reinforced composite materials can be noted in the last ten years. A recent review of jute-based polymer composites is presented in [12]. The scope of this paper is defined with woven jute fabric and thermoplastic matrices for developing laminate form of composites.

An extensive list of factors mentioned in the literature that affect the mechanical performance of the fibre reinforced polymer composites [5]. These factors can be classified based on (1) composite components (2) pre-processing of fibre (3) composite manufacturing and (4) composite internal condition as shown Figure 1.

For jute-based composites, different geometric structures such as fibre [14], sliver [15], yarn [16], woven or knitted fabric [17–22], and non-woven sheet [23] have been experimented as fillers in fabrication of composite materials, using both thermoplastic [18–20,23] and thermoset polymeric matrices [14,15,17]. Plain-woven structure [17–22,24] is most widely used in jute fabric reinforced composite manufacturing. From the manufacturing point of view, the use of woven jute fabric instead of unidirectional fibres to form laminate composite gives advantage of easy handling and controlling the layered structure with different orientations according to the requirements. Additionally, in comparison to short fibre or particle distribution in the matrix, the use of woven fabric can reduce the probability of fibre agglomeration or particle clustering while providing strength in both longitudinal and lateral directions. Contemporary research mostly focuses on single layer jute fabric as reinforcement in polymer composite materials, while sequential multilayer jute fabrics as reinforcement within thermoplastic matrices have not been studied sufficiently [19,25].

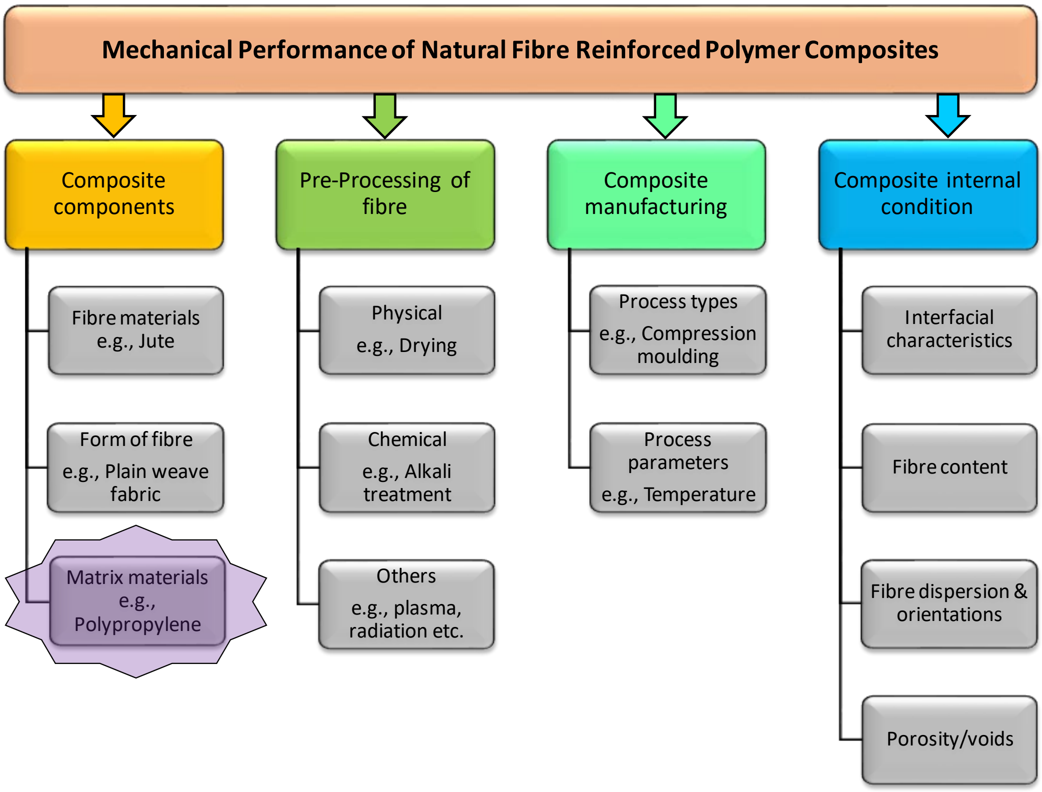


Figure 1. Factors affecting mechanical performance of NFRCs.

Matrix material is one of the most important element in thermoplastic composites. In general, the natural fibres start to degrade at approximately 200 °C [4] but it has been reported that untreated jute fibre degrades at a temperature range between 250-297 °C [26,27]. Therefore only the thermoplastic matrices, which have lower melting temperature than the jute degradation temperature would be suitable in the polymer composite system. The thermoplastic matrices—polypropylene (PP), polyethylene (PE), polyamides (PA), polyvinyl chloride (PVC) and poly lactic acid (PLA) are commonly used in NFRCs [24,28,29].

It is well known that poor interactions between the hydrophilic jute fibres and hydrophobic polymer matrices is one of the major drawbacks in polymer matrix composites. This results in a weak interface between the jute fibre and polymer, which is responsible for reducing the effectiveness of fibre's reinforcing function due to lack of load transfer from the matrix to the fibres. Different pretreatments of jute fabrics with alkali, plasma and polymeric coupling agents were recommended in different studies [30,31] for the improvement of mechanical performance of the resultant composite due to an increase in the interfacial adhesion between the jute fiber and thermoplastic matrices. Compression moulding has been reported as the most common technique for manufacturing jute reinforced thermoplastic composites even though other techniques such as extrusion and injection moulding are also highly popular [5]. After composite manufacturing, its internal conditions such as interfacial characteristics, fibre orientations etc. determine consistency in the mechanical performance.

Although HDPE is widely used in water and gas, food and packaging, and biomedical applications but it has lower mechanical properties than PP. Any improvement in mechanical properties with natural fibre reinforcement would be highly advantageous for increasing its envelop of applications. There are only a few of studies available in the literature on the layered woven jute fabric reinforced HDPE composite. An increase in tensile, flexural and interlaminar shearing strength was observed by Seki, et al. [19] in composite made from alkali and oligomer siloxane treated single layer of jute fabric compression moulded into two layers of high-density polyethylene (HDPE). Sayem, et. al [25, 32] developed composite laminates with jute hessian fabrics sandwiched in 0° orientation into several layers of High-Density Polyethylene (HDPE) polymeric sheets. 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% when compared to the pure HDPE laminates.

PP is one of the most studied matrix materials for manufacturing jute fibre based composite materials as it has suitable characteristics such as low density, good flexural strength, surface hardness, impact strength, easy moulding and dimensional stability [33]. A limited number of articles reported the investigation of jute fabric based layered PP composite. Berhanu [20] 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). Arju et al. [18] developed laminated composite by sandwiching one layer of jute fabric structures between two layers of PP sheets. The effect of different fabric structures with a fixed fibre weight percentage (55 ± 1%) was investigated and it was found that composites having a twill fabric structure showed 134% higher tensile strength than that of composites having a plain structure fabric.

Rahaman et al. [34] reported production of jute fabric reinforced composites with polypropylene (PP) and linear low-density polyethylene (LLDPE) reinforced with jute fabrics by compression molding technique. Better mechanical properties were observed in the polypropylene-based composites compared to that of LLDPE-based composite. Better mechanical properties of PP matrix was reasoned for this improvement, as the amount of jute was kept constant in both type of composites. A deceasing trend of mechanical properties were also observed under the effect increasing temperature from −18 °C to 50 °C.

Polyamide, also known as nylon, is widely used in engineering applications as it possess desirable mechanical and tribological properties such high stiffness, strength and wear resistance. Among various polyamides available, nylon 6 is considered one of the best choices as a matrix for composites [35]. Although no studies on nylon-jute composites were found in the literature but a natural fibre reinforced nylon composites are reported. Coconut shell (CS) particles and empty fruit bunch (EFB) fibres with different weight percentages were embedded in nylon-6 to develop novel natural fibre composites [36]. Only nylon-6/CS composite showed a moderate improvement in tensile strength but both composites showed an improvement in tensile modulus between 10% to 16%. The fracture surface morphology indicated a high compatibility between the fibres and matrix. Ozen et al., [28] produced natural fibers/ nylon 6 composites with three different fibres (kenaf, hemp and flax) and their blends by varying the natural fibres from 5 wt% to 20 wt% by injection moulding. All composites showed better tensile and flexural properties but poorer impact strength in comparison with the neat nylon 6. The reason for improvement was evidenced by efficient bonding occurred between the natural fibers and nylon 6. Comparable or higher mechanical properties were observed for 20 wt% of fiber blend composites than the composites with single fibers having same fibre weight percentage.

This paper investigates mechanical, water absorption and fracture properties of multilayer jute fabric reinforced composites with different thermoplastic polymer matrices. Three different matrices used in this study were High-Density polyethylene (HDPE), polypropylene (PP) and Nylon 6 as they are commonly available thermoplastic materials used in different structural applications and suitable for compression moulding. The investigation methodology of this research is presented in Figure 2. The originality of this work lies with the sequential impregnation of multilayer jute fabric within different thermoplastic matrices, which has not been addressed sufficiently in the literature [19, 25].

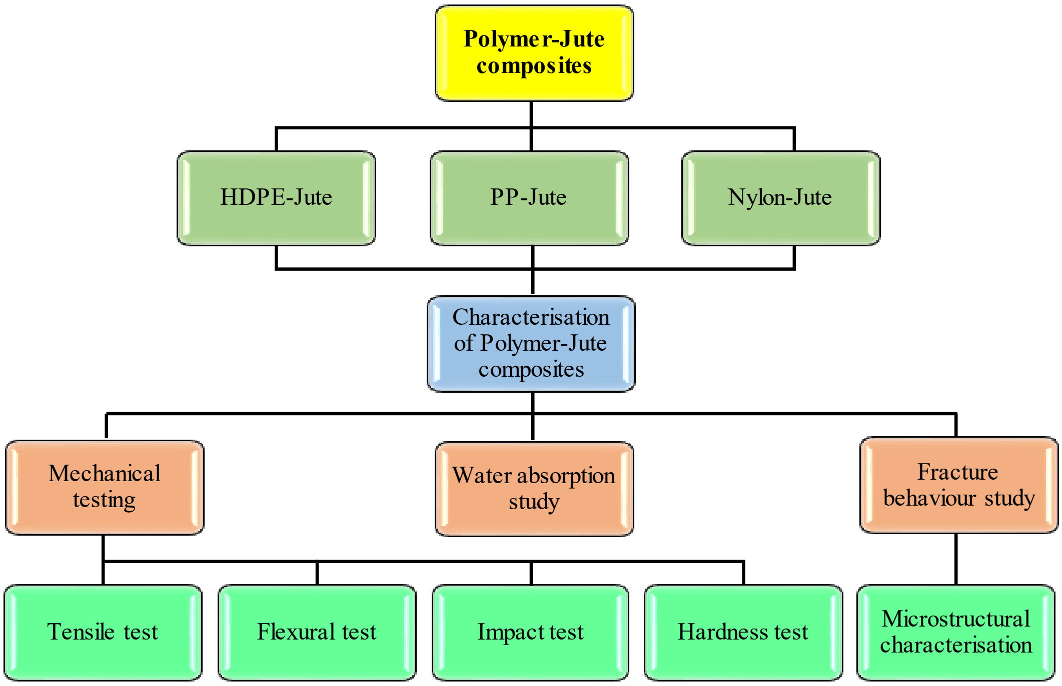


Figure 2. Strategy for the development and characterisation of Jute-reinforced thermoplastic composites.

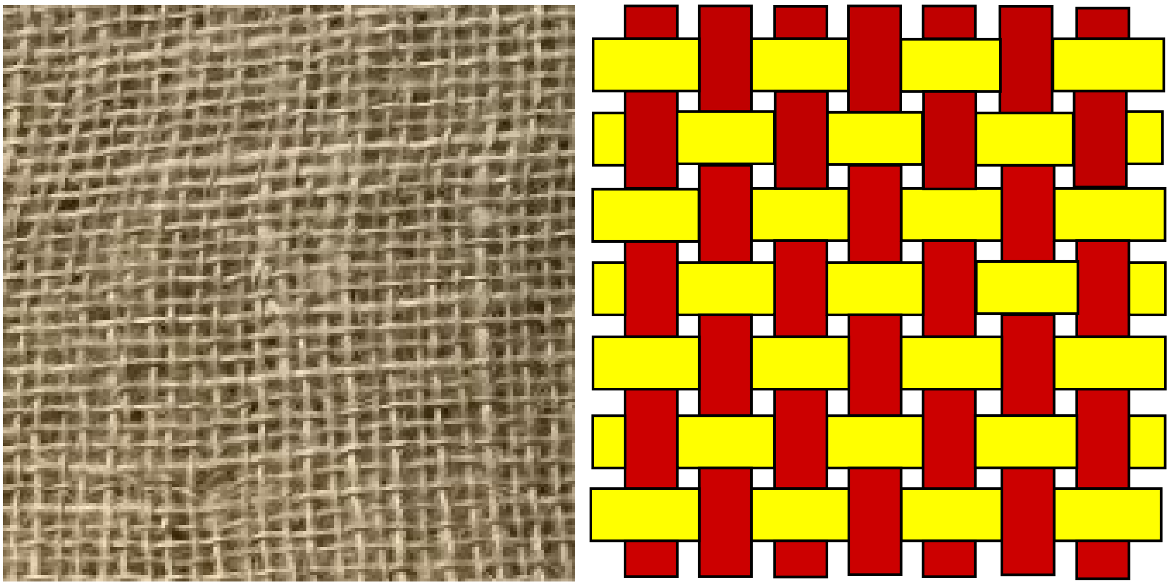
2. Materials and Methods

2.1. Raw Materials

The filler material used for manufacturing laminated polymer composites in this work was a 100% hessian fabric made of tossa jute collected from Janata Jute Mills Ltd. through Bangladesh Jute Research Institute (BJRI). Table 1 shows specification of the jute fabric and Figure 3 presents the jute fabric structure. HDPE, PP and Nylon 6 sheets with a thickness of approximately 1.0 ± 0.10 mm were purchased from Direct Plastics Ltd, Sheffield, UK and the general specifications of the thermoplastic sheets are presented in Table 2.

Table 1. Specification of jute fabrics.

Parameters	Value	Unit	Test Standards
Weave design	1/1 (plain)	-	BS EN 1049-2:1994
Warp	35	Ends per 100 mm	
Weft	31	Picks per 100 mm	
Weight	177	g/m2 (GSM)	BS 2471:2005



(a) (b)

Figure 3. (a) Jute fabric used in the composites and (b) the plain weave structure.

Table 2. Specifications of HDPE, Polypropylene and Nylon sheets [https://www.directplastics.co.uk].

Parameters	Unit	Values			Test Standards
		HDPE	PP	Nylon 6	
Colour	-	Natural			-
Density	g/cm³	0.947	0.905	1.14	-
Tensile Strength at yield	MPa	25	30	78	DIN/EN/ISO 527
Elongation at yield	%	9	8	4	
Hardness	Shore D	64	70	-	DIN/EN/ISO 868
Crystalline melting point	°C	130	165	-	DIN/EN/ISO 53736
Melting temperature	°C	-	-	221	DIN/EN/ISO 53765
Water absorption	%	<0.05	0.03	0.3	DIN/EN/ISO 62

2.2. Composite Fabrication

As jute fibre is hygroscopic in nature and has a high moisture content of 12% [7], the jute fabrics cut into square pieces of 175 mm × 175 mm were placed in an oven at 105 °C [37] for approximately 40 min to remove any moisture for avoiding any potential void formation in the composite laminates. However, no pre-treatment of the jute fabric was carried out. Plastic sheets were also cut into the same dimensions to form the laminate plate with alternate layer of jute and plastic. As soon as the dry jute fabrics were taken out from the oven, they were first weighed and then immediately stacked in between the plastic sheets according to the designs by hand lay-up technique 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 backing plates. Figure 4 shows the layup sequence of multilayer jute fabrics stacked at 0° orientation along the warp (i.e., lengthwise) direction between a total five layers of plastic sheets in order to maintain a constant thickness in all composites. Three different types of composite laminates (HDPE-Jute, PP-Jute and Nylon-Jute) were fabricated using 6 layers of dry jute fabrics in each case by hot pressing in a compression moulding machine (Bradley & Turton Ltd., Kidderminster, UK, Figure 5a) for 20 min at a temperature of 150 °C [37] for HDPE, 180 °C for polypropylene, and 250 °C for nylon with 6.2 MPa of pressure. For each of thermoplastic matrices, hot pressing temperature was selected slightly higher than its corresponding melting point to ensure good flow of matrix material around the fibres. Heat resistant Teflon sheets were placed between the staked structure and steel plates for easy release after hot pressing.

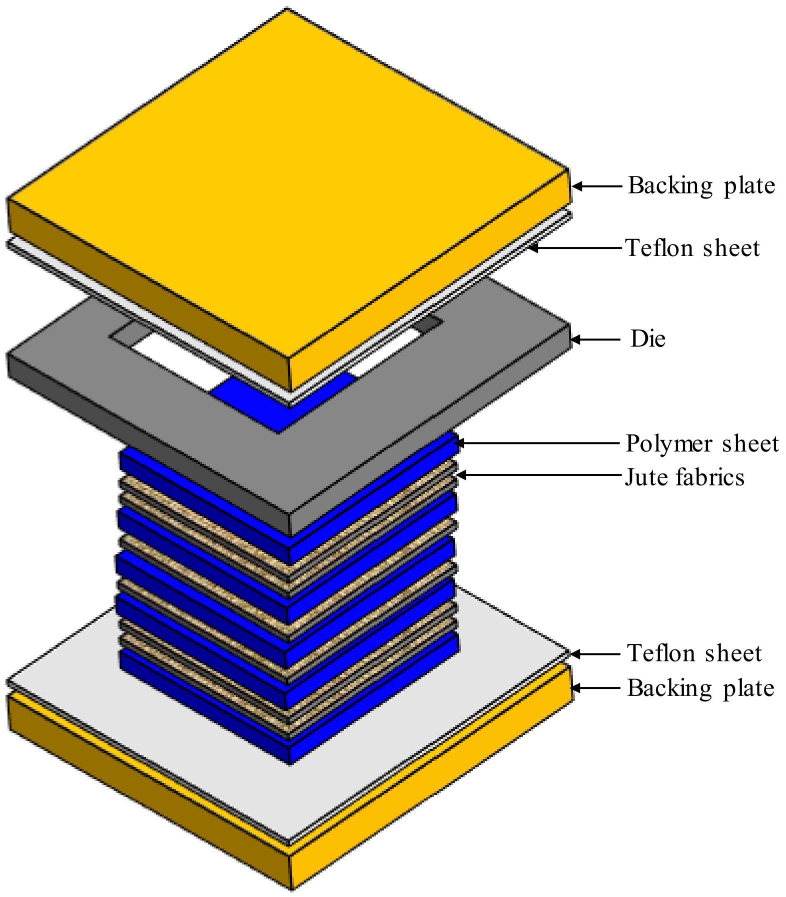


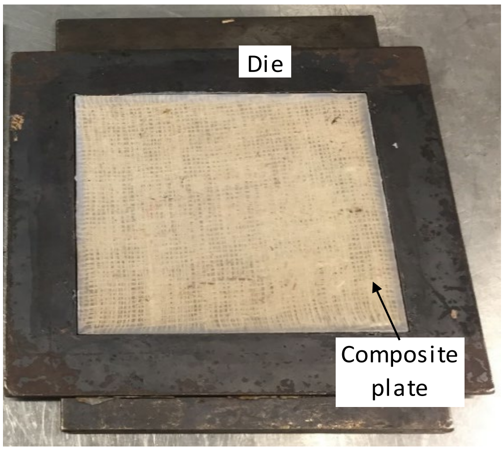
Figure 4. A schematic diagram of the layup sequence of multi-layered jute reinforced polymer composites with die arrangement for compression moulding.

After hot pressing, the composite laminate with the die was cooled to room temperature using a water-cooled press (Francis Shaw & Co., Manchester, UK) under a uniform pressure of 3.10 MPa for 10 min. Finally, the laminate was released from the die (Figure 5c), weighed for weight fraction calculation from the difference between the laminate weight and fabric weights using the following formula (Equation (1)).

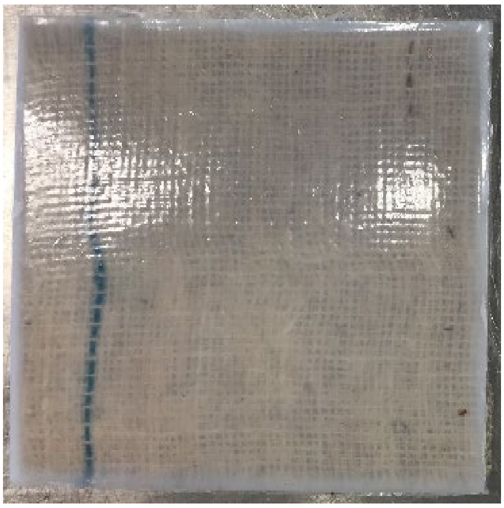
$$W_c = \frac{W_j}{W_p + W_j} \quad (1)$$

where W_c, W_j and W_p are the weight fractions of jute fabric in the polymer composite, weight of jute fabric and weight of polymer matrix respectively. The nominal content of jute fibre in the fabricated composite laminates was 18.0 ± 2.0 wt% (where, wt% means weight percentage). Even though the number of jute layers was maintained constant in all composites but the variations in overflow of the matrix materials out of the die during compression moulding under high pressure and temperature caused slight change in jute weight percentage. The laminates were cut in warp direction by a vertical bandsaw to prepare specimens for mechanical testing (Figure 5d). The specimens were deburred and polished in a grinding machine to remove any stress rising points.

(a)



(b)



(d) (c)

Figure 5. (a) Hot press for compression moulding (b) prepared jute-based composite with die (c) composite plate removed from the die and (d) cut samples with magnified surface view.

2.3. Mechanical Testing

Structure of the jute fabric and weight were determined following the standards BS EN 1049-2:1994 and BS 2471:2005 respectively. The breaking force 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.

Tensile testing of the composite specimens was carried out on Hounsfield H10 KS Tensometer equipped with a 10,000 N load cell, according to ASTM D-3039. The cross-head speed used for the tensile specimens was 2 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 used for tensile and flexural testing. However, the dimensions of individual test specimens were measured during every test and entered into the software for the accurate measurement of the strengths. The tensile tests of the composite specimens 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 [21]. Tensile stress (σ) and strain (ε) were calculated from the test data using Equations (2) and (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 the amount of extension. Young's modulus was calculated from the initial slope of the stress-strain curve using Equation 4.

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

The flexural strengths and moduli of the composite specimens were measured using a three-point bending test according to ASTM D790-02: 2002 test standard 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 2 mm/min. The flexural strength (σ_f), strain (ε_f) and modulus (E_f) were calculated using Equations (5–7) respectively.

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

$$\epsilon_f = \frac{6sd}{L^2} \tag{6}$$

$$E_f = \frac{mL^3}{4bd^3} \tag{7}$$

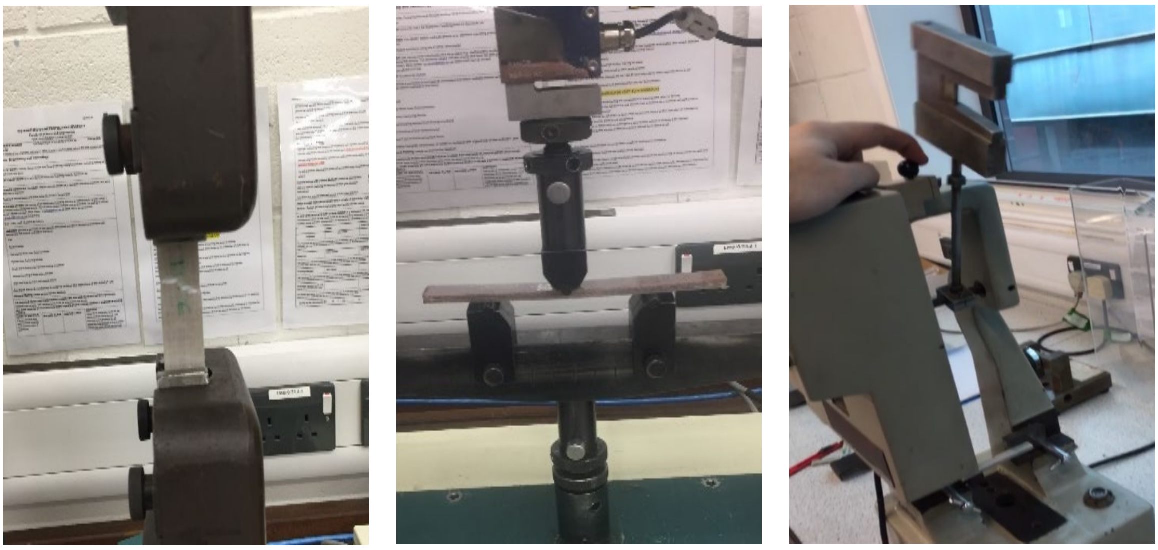
where F is the applied load (N), L is the span length (mm), b is the specimen width (mm), d is the specimen thickness (mm), s is the measured deflection and m is the slope of the initial straight-line portion of the load-deflection curve.

The Charpy impact test was conducted using a Zwick pendulum impact-testing machine. The load of the pendulum was 4 J. This test measures the toughness of a material. The impact properties were measured according to ISO 179-1:2010 test standard. The specimen was placed on a sample holder near the base of the machine with the un-notched side facing the striking edge of the impact pendulum. The pendulum was released to hit along the notch edge of the sample and the energy required to break the sample was recorded from the test machine. The impact strength (σ_I) of the specimens were calculated by dividing the impact energy (E_I) with broken cross-sectional area (Equation (8)).

$$\sigma_I = \frac{E_I}{d(b - d_n)} \quad (8)$$

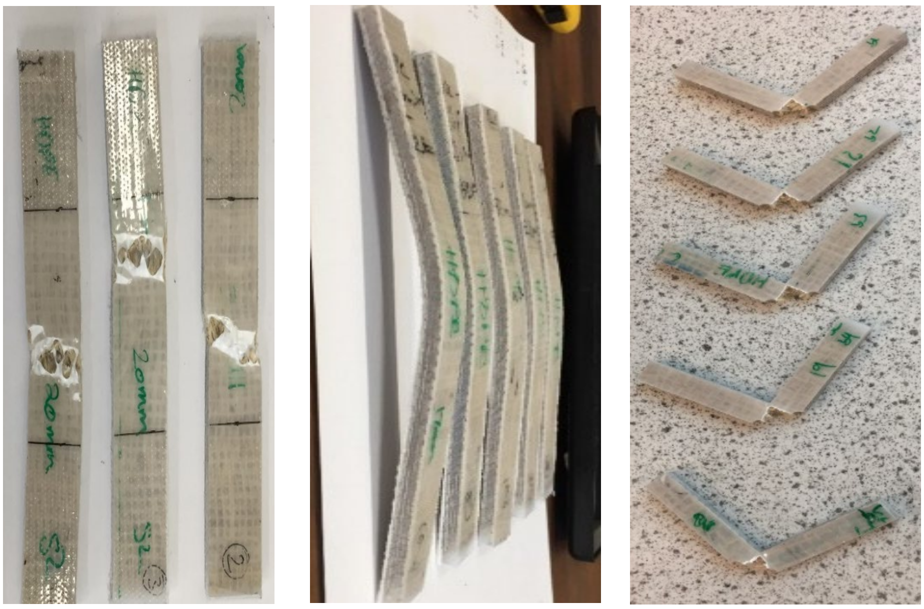
where d_n is the notch depth.

Figures 6 and Figure 7 present the arrangements of different mechanical tests and the corresponding representative samples after the tests respectively.



(a) (b) (c)

Figure 6. Experimental arrangements for (a) Tensile (b) Flexural and (c) Impact tests.



(a) (b) (c)

Figure 7. Test samples after different mechanical tests: (a) Tensile (b) Flexural and (c) Impact tests

Hardness test was conducted according to ISO 868: 2003 test standard using a shore D hardness tester to find out the hardness of the composite materials. Under specified conditions of force and time the indenter was penetrated into the materials. The instrument was placed on the surface of and parallel to the material being tested. The hardness readings were taken at 10 different points along the specimen length and the readings for each specimen were averaged.

All mechanical tests were repeated on five specimens for each type of composites and average results with standard deviations were reported.

2.4. Water Absorption Test

The water absorption tests of jute fibre reinforced polymer composites were conducted by immersing them in distilled water at room temperature. The specimens were taken out periodically and after wiping out the water from the surface with a paper towel and were weighed immediately to find out the content of water absorbed. The specimens were weighed regularly at Day-1, Day-3 and Day-7. The water absorption is calculated by the weight difference between the dry and wet samples. The percentage water gain by the specimens was measured at different time intervals using Equation (9).

$$Water\ absorption\ (W\%) = \frac{W_2 - W_1}{W_1} \times 100 \tag{9}$$

where, W% is the percentage of water absorbed, W_2 is the weight of composite specimen (gm), after immersing in water, W_1 is the weight of dry composite (gm) before immersing in water.

2.5. Microscopic Observation

The cross-sectional views of the composite specimens were observed in an optical microscope to check the jute yarn orientation and layer positions within the composites. The cut and fractured surfaces of the composites were also observed under a scanning electron microscope (SEM) to analyse the adhesion and interfacial characteristics between the jute fibres and the matrices. An SEM of model JSM-5600LV from JEOL Ltd. was used at an accelerating voltage equal to 20 kV in secondary electron mode.

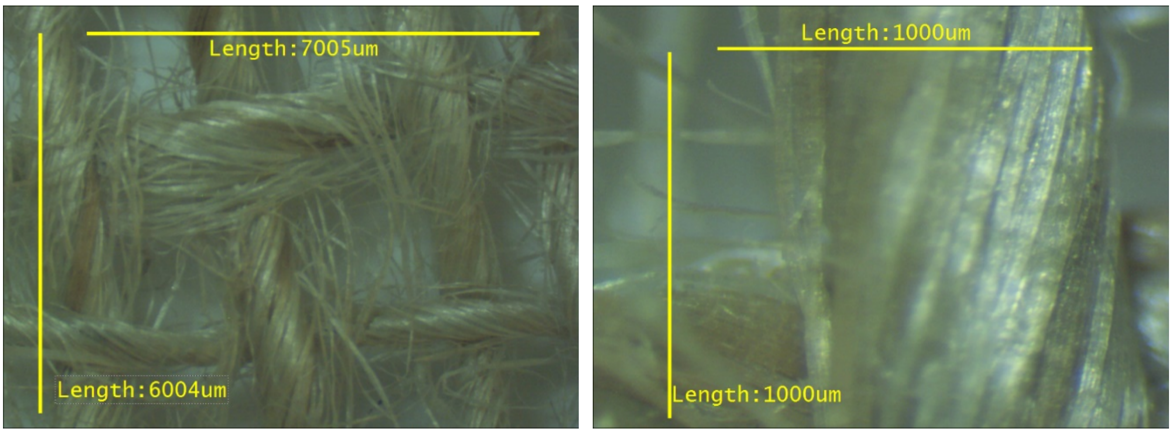
3. Results and Discussions

3.1. Characteristics of Jute Fabric and Composites

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 (Figure 8). Some degree of non-uniformity in the diameter of the yarn and gap between the yarns were also observed. It was clear from the breaking force tests results presented in Table 3 that average breaking force was approximately 20% higher in the warp direction compared to that in the weft direction. The results agreed with the values mentioned in the literature [22]. On the other hand, average breaking extension was 10% higher in the warp direction. Even though jute fibre had high strength, its failure mode was observed as brittle fracture [22]. Furthermore, the fibres broke only by small extension ranging from 8.23%–9.03% indicating a low elastic property.

Table 3. Tensile properties of jute fabric.

Parameters	Measured Values with standard deviations	Unit
Average Breaking force Warp	392.1 ± 48.7	Newton
Average Breaking force Weft	325.7 ± 31.5	Newton
Average Breaking Extension Warp	18.1 ± 6.2	mm
Average Breaking Extension Weft	16.4 ± 1.7	mm
%Average Breaking Extension Warp	9.03 ± 3.1	%
%Average Breaking Extension Weft	8.23 ± 0.86	%



(a) (b)

Figure 8. Magnified images of jute (a) fabrics and (b) fibres in a yarn from the same fabric.

Even after high compression moulding process, the composites maintained the layered structure with evenly spaced jute fabrics within the matrices as observed in the cross-sectional views of the specimens (Figure 9a). The specimens were also free from any visible voids or air bubbles across the thickness and the jute layers were completely immersed within the matrices. The cut surface images (Figure 9b–d) of all three composites at much higher magnification also showed that polymer materials flowed around the yarns with no voids in the matrices. However, the polymer matrices could not completely wet the fibre bundle in the yarns leaving gaps in the bundles. These characteristics of the composites clearly demonstrated their superior quality in terms of composite design and structural integrity.

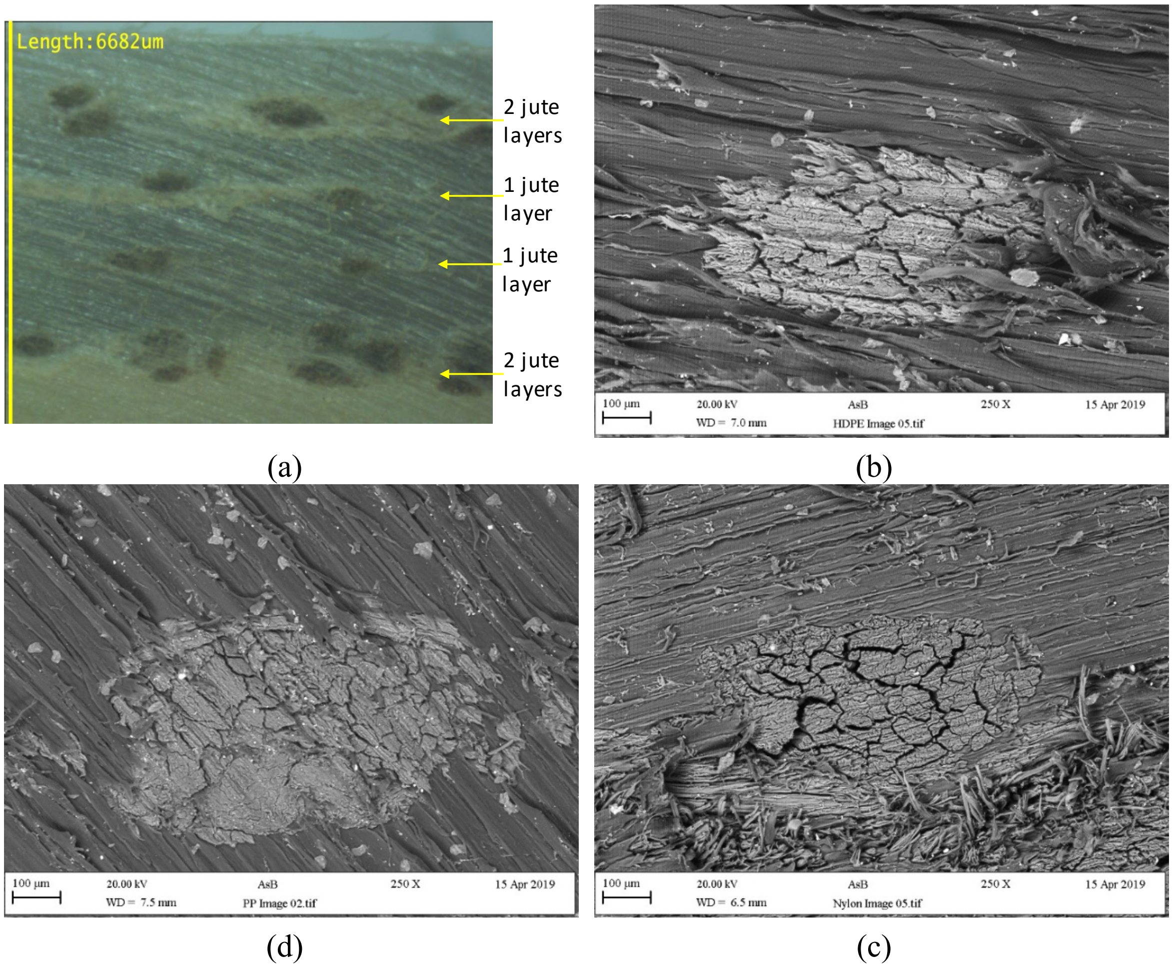


Figure 9. (a) Optical image of cross-section across laminate thickness and SEM images of composite cut surfaces: (b) HDPE-Jute, (c) PP-Jute and (d) Nylon-Jute.

3.2. Tensile Strength Tests

Figure 10 presents typical stress-strain curves for HDPE-Jute, PP-Jute and Nylon-Jute with gradually increasing slopes and maximum stresses indicating an increase in stiffness and strength respectively. For each material, slopes of the initial portion of each curve decreased with a step change until the peak stress. This indicated a transition from linear to non-linear material behaviour. This could be due to initial crack development within the matrix followed by progressive fibre pull-out or fibre failure [21,22]. The change in slope is maximum for HDPE-Jute composite and minimum for Nylon-Jute composite indicating a more ductile to less ductile behaviour of the materials. This change in material behavior was also seen in Figure 11, where the extensions at peak forces gradually decreased from HDPE-Jute to PP-Jute to Nylon-Jute composites.

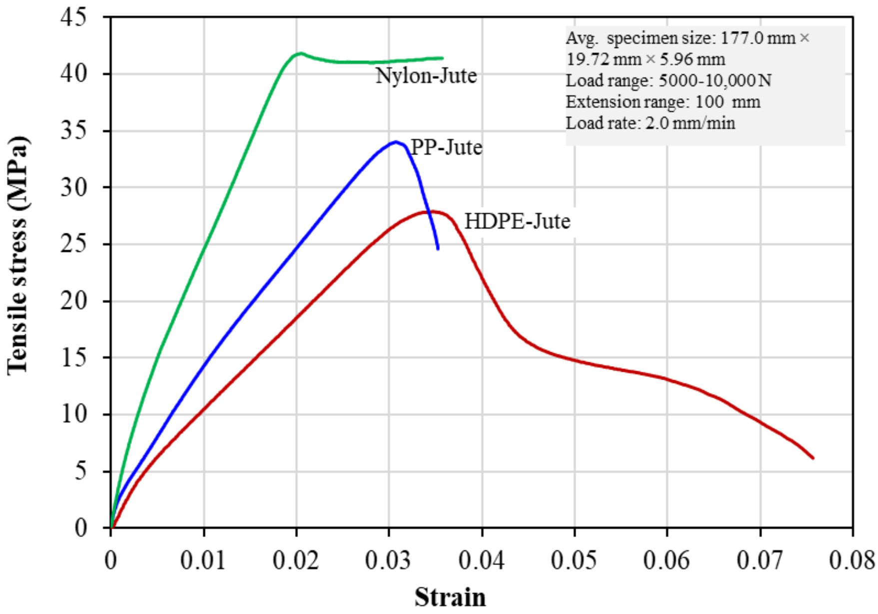


Figure 10. Tensile stress-strain curves for different jute-based composites.

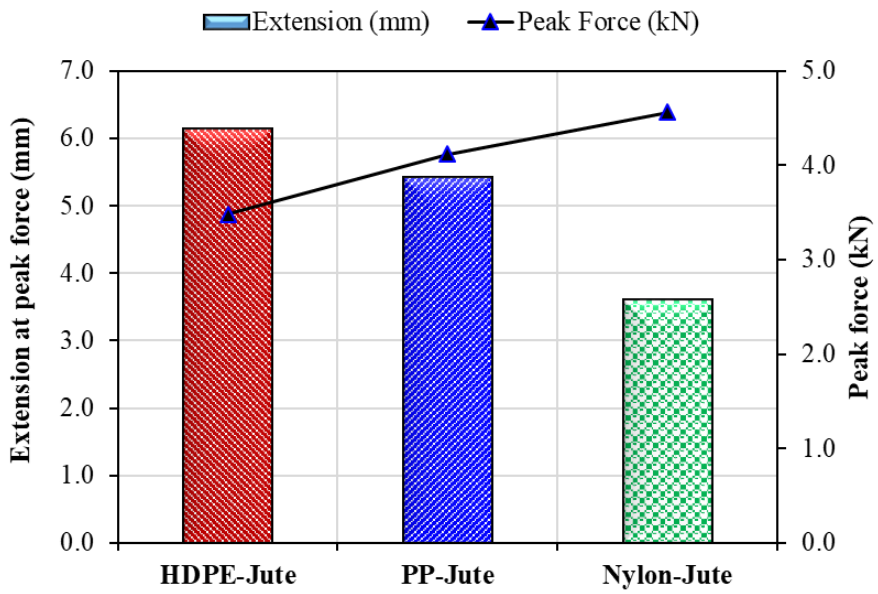


Figure 11. Extensions at peak forces for different jute-based composites during tensile testing.

Figure 12 presents the tensile test results of three different composites having six layers of jute fabric reinforcement in each case. Tensile strength values of the HDPE-Jute, PP-Jute and Nylon-Jute were found as 27.98 MPa, 34.25 MPa and 40.62 MPa respectively. This indicated that the PP-Jute and Nylon-Jute composites prepared in this research work were 22.43% and 45.20% respectively stronger than the HDPE-Jute composite. As the fibre weight percentage in all three composites were approximately same, the change in tensile strength of the composites could be attributed to the properties of the matrices and interfacial characteristics as reported by other researchers in the literature [34]. The mechanical properties of jute fiber were much higher than the matrices [4]. The transfer of load from the matrix to the fibre was occurred during testing could contribute to the improvement in tensile strength [34]. When compared to the pure HDPE and PP matrices, the corresponding composites showed an improvement in tensile strengths by approximately 12%, and 14% while the Nylon composites showed a reduction in strength by 48%.

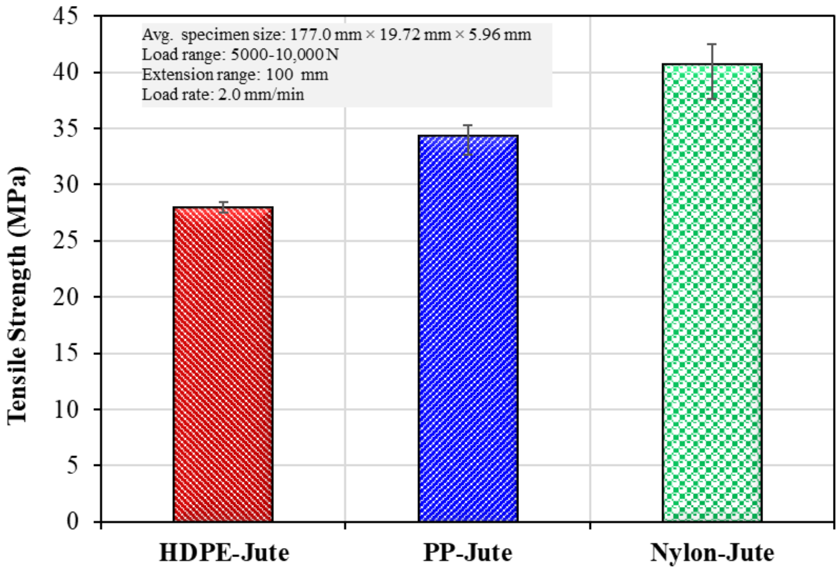


Figure 12. Tensile strength of three different composites in warp direction.

Young's moduli of HDPE-Jute, PP-Jute and Nylon-Jute composites were found as 2.03 GPa, 2.38 GPa and 3.79 GPa respectively as presented in Figure 13. Therefore, PP-Jute and Nylon-Jute composites were 17.48% and 86.72% stiffer than the HDPE-Jute composite respectively. From the results obtained, as expected the Nylon-Jute composite showed the best tensile properties followed by the PP-Jute and HDPE-Jute composites.

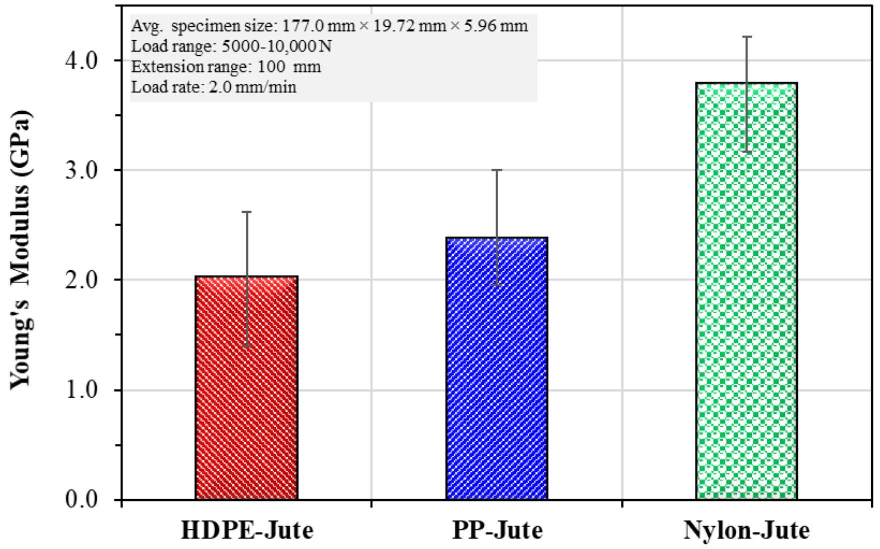


Figure 13. Comparison of Young's moduli of the jute-based polymer composites.

3.3. Flexural Strength Tests

Figure 14 presents representative flexural stress-strain curves for different jute-based composites. Typical nonlinear stress-strain behavior was found for all the composites. With the change of matrices from HDPE to PP to Nylon, the ability to resist the bending of the composites gradually increased as indicated by the rising change in slope of the curves. At the peak compressive loading, no breaking of the composite specimens was observed. For Nylon-Jute composite, a series of secondary flexural strength behavior was observed. Similar behaviour was also observed for other composites reported in the literature [38].

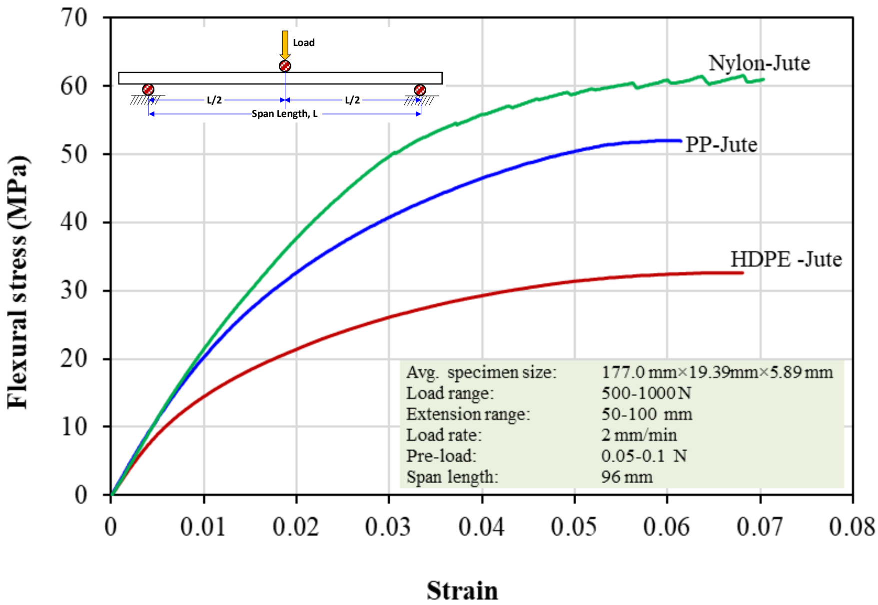


Figure 14. Flexural stress-strain curves for different jute-based composites.

Average flexural strength values of HDPE-Jute, PP-Jute and Nylon-Jute composites were found as 33.23 MPa, 52.66 MPa and 62.47 MPa respectively, as shown in Figure 15. This indicated that the flexural strengths of PP-Jute and Nylon-Jute composites were respectively 58.49% and 88.01% higher than that of the HDPE-Jute composite. In addition, Nylon-Jute composite possessed 18.62% higher flexural strength than the PP-Jute composite.

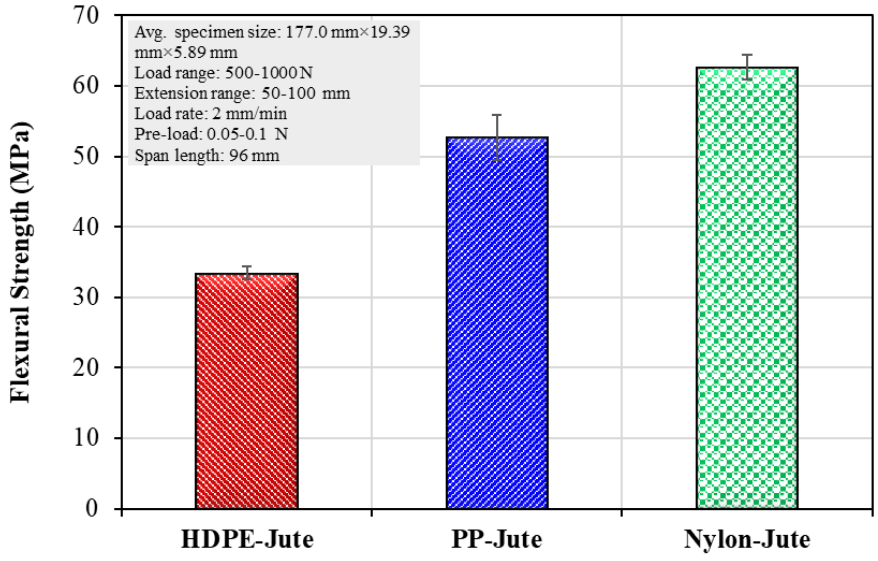


Figure 15. Comparison of flexural strengths for different jute-based polymer composites.

Figure 16 shows average flexural modulus values of 1.84 GPa, 2.32 GPa and 2.36 GPa for HDPE-Jute, PP-Jute and Nylon-Jute composites respectively. The flexural stiffness of PP-Jute and Nylon-Jute composites were respectively 26.32% and 28.49% higher than that of the HDPE-Jute composite. However, there was not much difference in flexural modulus between the Nylon-Jute and PP-Jute composites with larger range of variation in the later. For all the composites, the flexural strengths were higher than the tensile strengths, which could be found in majority of the studies in the literature [18,20].

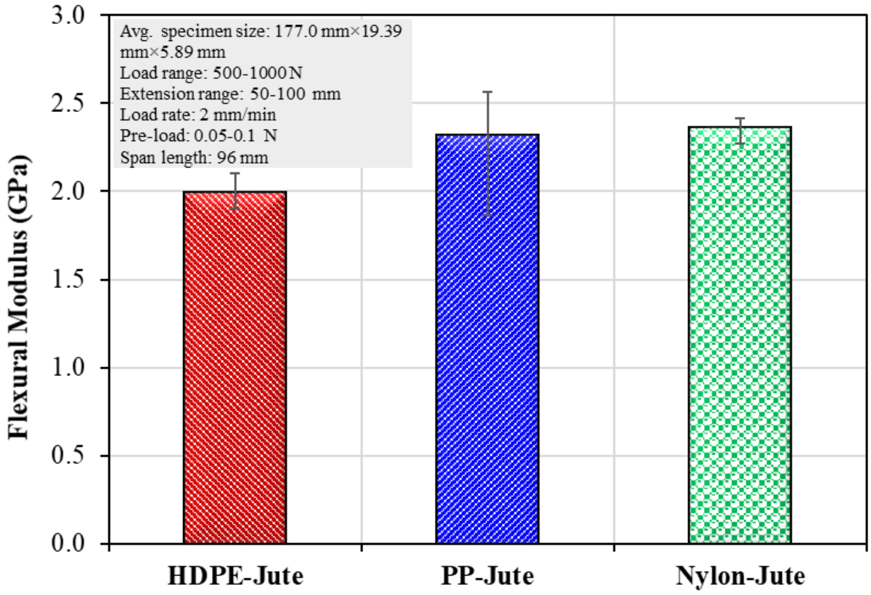


Figure 16. Comparison of flexural moduli for different jute-based polymer composites.

In summary, as Nylon-Jute composite showed highest flexural strength and modulus, it would deflect lesser than the other composites under bending loading condition.

3.3. Impact Strength Tests

Impact strength is one of the deciding factors in material selection as it measures the ability of a material to absorb energy before it breaks. Impact strengths of the HDPE-Jute, PP-Jute and Nylon-Jute composites are presented in Figure 17. HDPE-Jute clearly produced the best impact property with 78% and 82% higher impact energies than the PP-Jute and Nylon-Jute composites respectively. For all the composites specimens were completely broken during the impact tests making the results more consistent across the different materials tested. Visual analysis of the fractured specimens clearly indicated ductile fracture tendency in HDPE-Jute and PP-Jute composites and less ductile fracture in Nylon-Jute composite. The impact energy values obtained during the tests also support these observations. Higher impact strength was also reported for LLDPE-Jute composite by Rahaman et al. when compared to the PP-Jute composite [34]. It has been reported that addition of natural fibres (Hemp, flax and Kenaf) by 20 wt% to nylon 6 can reduce the impact strength between 40% to 50%. Crack propagation at the fibre matrix interface was reasoned for the reduction in impact strength [28]. More detailed analysis of the fractured surfaces will be presented in a later section.

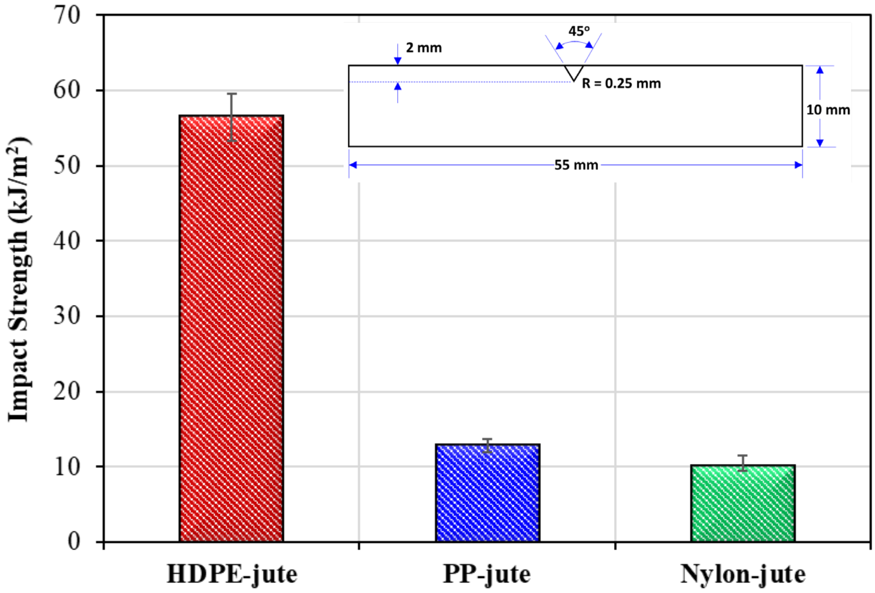


Figure 17. Impact strengths of jute reinforced composites with HDPE, PP and Nylon matrices.

It is interesting to note that the jute fibres in the Nylon matrix appeared slightly darker as if they were burnt. Relatively higher processing temperature during fabrication of the Nylon-Jute composite could affect the jute fibre strength. This could be another contributing factor for the reduction in impact strength. However, it was not very clear why the impact strength value of the PP-Jute composite was similar to Nylon-Jute composite even with some degree of ductile fracture characteristics. Higher hardness of PP closer to Nylon and the state of crystalline structure after the compression moulding and fiber matrix interfacial condition could be responsible for poor impact strength compared to HDPE-Jute composite.

3.4. Hardness Tests

Figure 18 presents the hardness tests results conducted on the jute-based composites. The hardness of the nylon-Jute composite was found to be the highest, followed by the PP-Jute and HDPE-Jute composites. There was a 21% increase in the hardness between the composites with HDPE and PP matrices. Furthermore, there was a 7% increase in the hardness between the composites with PP and nylon matrices. The variations in hardness among the composites could be due to the influence of the matrix materials as they possess similar trend of hardness variation. The highest hardness in the nylon-Jute composite could be related to its lowest impact strength (see Figure 17) as higher hardness induced more brittleness in the materials. For the other two composites, similar relationship between the hardness and impact strength was also observed.

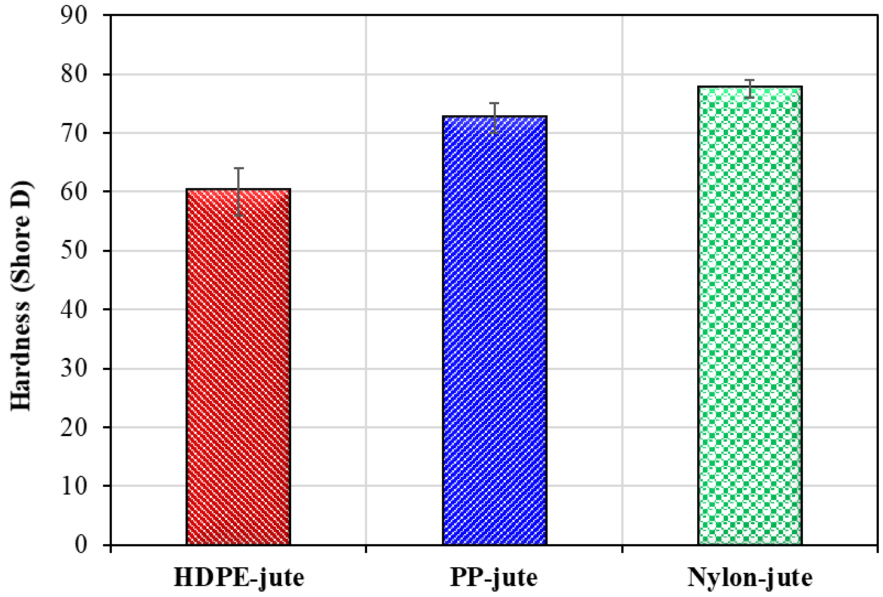


Figure 18. Hardness of jute reinforced composites with HDPE, PP and Nylon matrices.

3.5. Water absorption tests

Water absorption performance of a composite is defined by the amount of water absorbed within a certain time. The higher the amount of water absorbed, the poorer the performance is. Water absorption performance is related to the dimensional stability of the composites. Figure 19 shows weight percentages of water absorption by the composites at different time intervals. The percentage of water absorbed after 1 day was highest for the HDPE-Jute composite at 5.51%, followed by the Nylon-Jute composite with closer results of 5.37% and the PP-Jute composite at 2.82% having the lowest percentage of water absorption. However, after 3 days, the Nylon-Jute composite absorbed the highest percentage of water at 8.60% followed by the HDPE-Jute composite at 6.4% and the PP-Jute composite with the lowest percentage of water at 3.83%. Furthermore, after 7 days the Nylon-Jute composite still absorbed the highest percentage of water at 10.72% and the PP-jute composite absorbed the lowest percentage of water at 4.65%. In general, the water absorption performances of the composites can be ranked from best to worst in the following order: PP-Jute > HDPE-Jute > Nylon-Jute. The higher percentage of water absorption by Nylon-Jute composite can be related to its moisture sensitivity [35,36]. It was previously reported that jute reinforced composite materials reached water saturation in 24 hours [31,39]. It is interesting to note that after 7 days the composites did not reach complete saturation stage, although the maximum increase in water absorption from Day-3 to Day-7 was not significant (only 2%).

The presence of hydroxyl (–OH) group in the jute fiber structure makes it hydrophilic in nature and swelling of the fibres occur through absorbing huge amount of water. It has been reported that pure hessian jute fabric can absorb water as high as 90% within an hour [34,37]. In the composites, water is absorbed by the jute fibre through the cut edges. Relatively small amount of water is absorbed in the composites as the jute fibres are tightly bonded within the matrix and coated with hydrophobic polymers such as HDPE and PP [34].

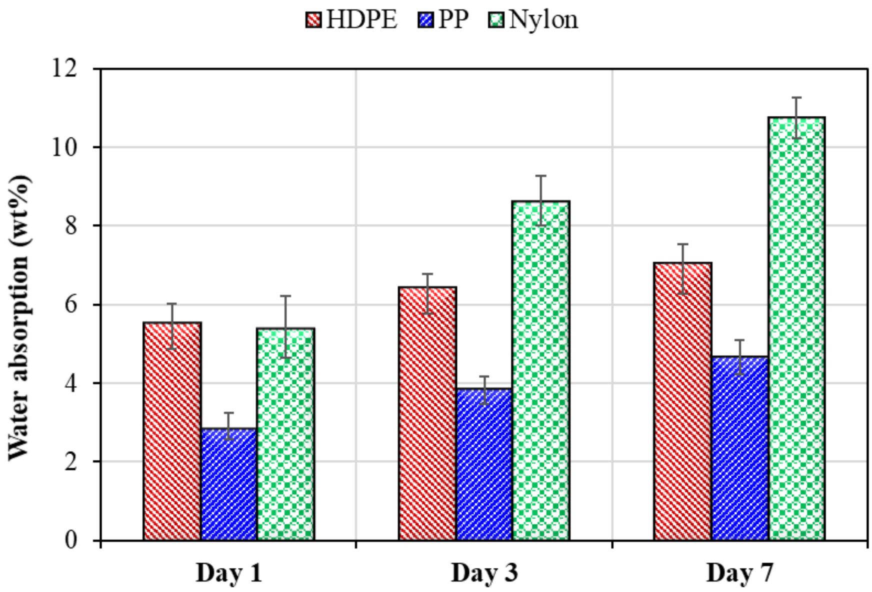
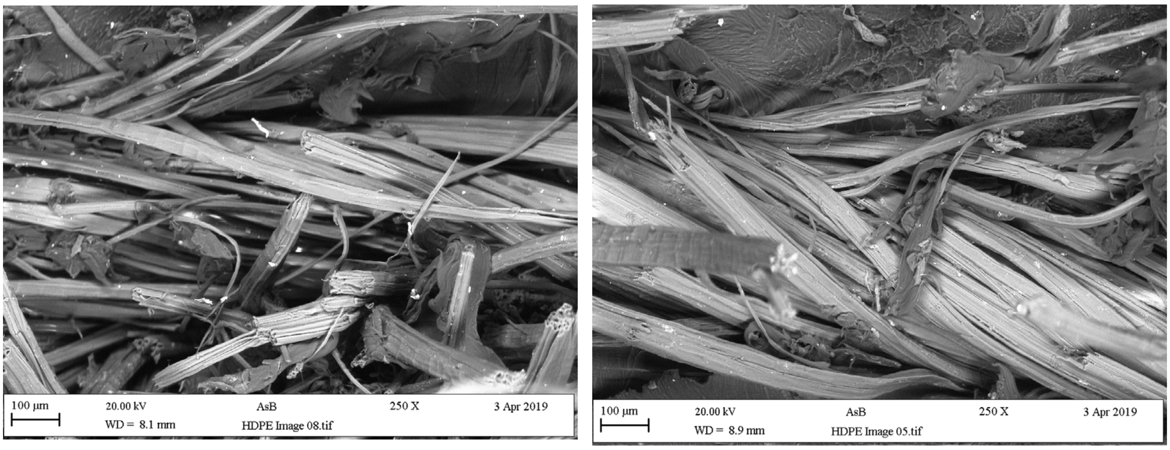


Figure 19. Water absorption of jute reinforced composites with HDPE, PP and Nylon matrices.

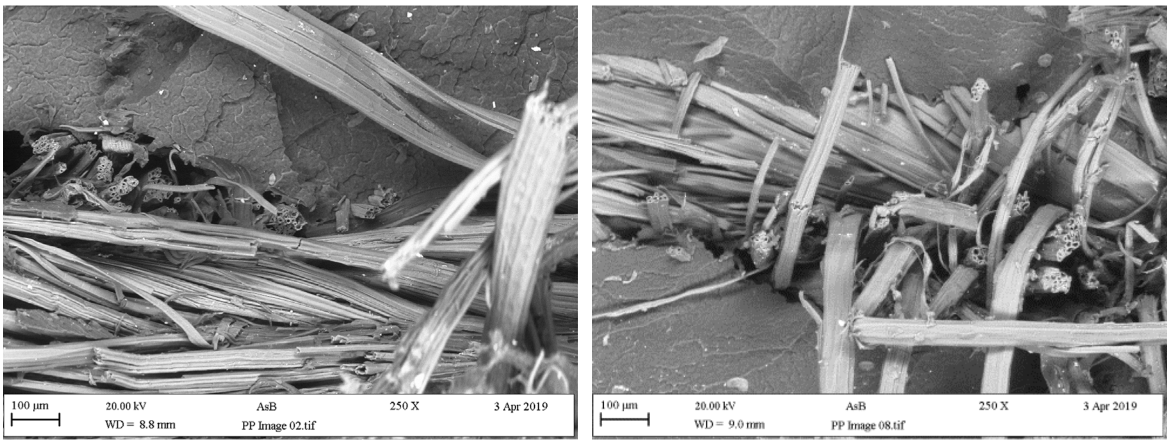
3.6. Interfacial Surface Morphology

The fractured surfaces of the jute fabric reinforced polymer composites from the impact tests were observed under the SEM to analyse the adhesion and interfacial characteristics between the jute fabrics and polymer matrices at two different points as shown in Figures 20–22. It was clear from the analysis that the interaction between the jute fabric and matrices was strongest for the HDPE-Jute and weakest for the Nylon-Jute composite, which could be one of the contributing factors for the variations in composite strength. In the HDPE-Jute composite, many outer jute fibres of a yarn were seen interacting with the matrix indicating a good adhesion. However, the inner fibre surfaces in the yarns were relatively clean indicating poor fibre/matrix interactions leading to a poor stress transfer from the matrix to the fibre. Gaps were also observed within the fibre bundle indicating that the fibres were not fully wet by the matrix materials. These observations were aligned to what was observed in [20]. Similar behaviour was also observed for the PP-Jute composite but the interaction between the fibre and matrix was clearly weaker than the HDPE-Jute composite. On the other hand, Nylon-Jute composite did not show any hair like jute fibres on the fractured surface. Fiber rupture and pull-out were predominant mechanisms in the HDPE-Jute and PP-Jute composites. However, clean fracture of the jute fibres with no fibre pull out was clearly seen in the Nylon-Jute composite similar to what is reported by Ozen, et al. [28]. The processing temperature of Nylon-Jute composite (250 °C) was much higher than the other two composites. At this temperature the jute fibre possibly started to degrade [26,27], which might have affected the jute fibre strength characteristics and fracture of the fibres were observed in the Nylon-Jute composites. In summary, the fracture behavior of the HDPE-Jute and PP-Jute composites were characterised by fibre pull out compared to the clean breaking of fibres in the Nylon-Jute composite. This could be the reason for relatively lower impact strength found in the Nylon-Jute composite.



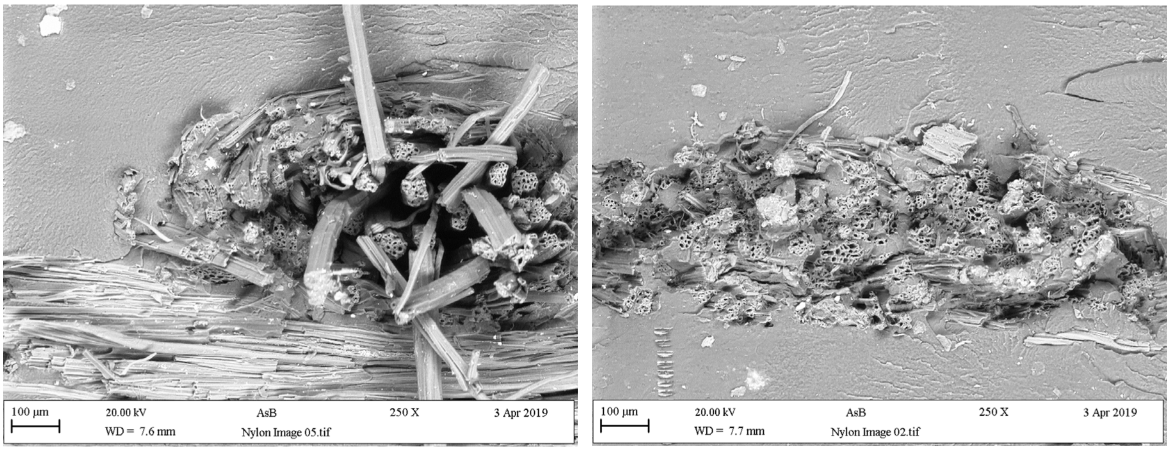
(a) (b)

Figure 20. SEM pictures of fractured surfaces from HDPE-Jute composite.



(a) (b)

Figure 21. SEM pictures of fractured surfaces from PP-Jute composite.



(a) (b)

Figure 22. SEM pictures of fractured surfaces from Nylon-Jute composite.

4. Conclusions

Jute-fabric based layered polymer composites were prepared using three different polymer matrices with compression moulding techniques at a nominal fibre content of 18 wt%. High quality layered jute composites were obtained with all three matrices as evidenced by clearly separated fabric layers immersed across the laminate thickness with no visible voids. In terms of majority of the mechanical properties such as hardness, tensile strength, Young's modulus, extension at maximum force, flexural strength and flexural modulus, the composites can be ranked in the following order: Nylon-Jute > PP-Jute > HDPE-Jute. However, HDPE-Jute composite displayed the best impact behavior among the composites possibly due to maximum interaction of the jute fibres with the ductile nature of the matrix. Water absorption tests showed that PP-Jute composite absorbs the smallest amount of water compared to the other composites. Good adhesion with the jute fabric in the matrices were also observed in the magnified images of the cut surfaces. Ductile failures for HDPE-Jute and PP-Jute composites and a tendency of brittle failure for Nylon-Jute composite were observed in the fractured specimens under impact loading condition possibly due to the nature of matrices and fibre-matrix interaction.

Therefore, based on the material application requirements with moderate tensile and flexural properties, high impact properties and low cost, HDPE-Jute composite would be the ideal choice for use. Whereas, if the impact strength and cost are not the major concerns, Nylon-Jute composite is the best choice among the composites with highest tensile and flexural properties.

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