Mechanical Properties of Surface Modified Jute Fibre/Polypropylene Nonwoven Composites

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Abstract: In this study, the jute/polypropylene nonwoven reinforced composites were prepared using film stacking method. The surface of jute fibres was modified using alkali treatment. These alkali treated jute fibre nonwoven composites were analysed for their tensile and flexural properties. Increasing the amount of jute fibres in the nonwoven reinforced composites has improved their mechanical properties. The effect of stacking sequence of preferentially and non-preferentially oriented nonwovens within the composites was also analysed. The flexural and tensile moduli of composites were found to be significantly enhanced when nonwovens consisting of preferentially and non-preferentially aligned jute fibres were stacked in an alternate manner.

Keywords**: Fibres, Mechanical properties, Compression moulding, Surface treatments**

1. INTRODUCTION

Natural fibre reinforced composites not only offer environmental and economical benefits but they exhibit high strength to weight ratio, lower density, nonabrasive behaviour, lower energy requirement to processing, good calorific value, and acceptable mechanical and thermal properties. These advantages of natural fibre composites have noticeably attracted attention of automotive, building and construction industries [1-3]. In the past, the natural fibres such as jute, flax, hemp, sisal, coir, etc. have been used as reinforcement in composites amongst which jute fibre based composites had moderate tensile and flexural properties [4-6]. In general, the jute fibres are complex heterogeneous lignocellulosic polymers composed of cellulose, hemicellulose and lignin that contain polarized hydroxyl groups. These hydroxyl groups cause inevitable bottle-necks when jute fibres are used as reinforcement in combination with hydrophobic matrices [7]. Thus, the jute fibres need to be treated physically or chemically in order to obtain good interfacial adhesion with hydrophobic polymer matrix. Polypropylene (PP) is a commonly used matrix for fabrication of composites containing jute fibres primarily due to its lower processing temperature, lower cost and added advantage of recyclability [8-10]. Various studies have focused on the surface modification of jute fibres in order to enhance the interfacial adhesion characteristics with polypropylene matrix [11-15]. Alkali treatment of jute fibres can significantly improve the compatibility with polypropylene as the number of hydroxyl groups is eliminated leading to enhancement in the mechanical properties of composites [16].

Jute fibres can be used as reinforcement in various forms including chopped fibres, yarns, and fabrics (woven, knitted or nonwoven). Recently, nonwovens have emerged as a promising candidate for reinforcement applications primarily due to good combination of light weight, lower production cost and flexibility compared to conventional materials [16-18]. Nonwoven formation involves aligning the fibres randomly or directionally and subsequently, bonding these fibres by chemical, mechanical, or thermal means. This technique of producing fabric not only eliminates the processes such as spinning, weaving or knitting but allows a range of fibre alignment that can be easily controlled. Miao and Shan [19] have successfully fabricated composites consisting of highly aligned nonwoven mats that exhibit similar mechanical properties as that of unidirectional fabrics. Therefore, the main objective of the present paper is to prepare and analyse the mechanical properties of jute/PP nonwoven reinforced composites. The surface of jute fibres has been modified by alkali treatment in order to enhance the compatibility with the PP matrix. Furthermore, the effect of stacking sequence of preferentially and non-preferentially aligned nonwovens within the composites has been investigated. The mechanical properties of nonwoven composites can be tailor-made by appropriately stacking the preferentially and non-preferentially aligned nonwovens in various sequences.

2. EXPERIMENTAL

2.1 Materials

Tossa jute fibres (*Corchorus olitorius*) of BTC (Bangla Tossa C) grade were provided by Bangladesh Jute Research Institute (BJRI), Dhaka, Bangladesh. Sodium hydroxide (NaOH) pellets of 98% purity were supplied by Merck, Germany for alkali treatment of jute fibres. The jute fibres were treated with alkali based on the methodology developed by Saha et al. [20]. In this study, the jute fibres were cut into 51 mm of length, washed with distilled water and oven dried for obtaining a constant weight. These jute fibres were then treated with 4 wt.% NaOH solution at ambient temperature (30 ± 2 ºC) for 30 min duration in order to maintain a constant fibre weight to liquor ratio of 1: 50 (w/v). These fibres were then neutralised with 5 wt.% acetic acid solution and subsequently, washed with distilled water. The jute fibres were air dried at a room temperature for 24 hours and then oven dried to obtain a constant weight. Fifty untreated and alkali treated jute fibres were tested for tensile testing conforming to ASTM D3822-07. The constituent fibre properties of polypropylene, untreated and alkali treated jute fibres are given in Table 1.

2.2 *Preparation and characterisation of alkali treated jute/polypropylene blended nonwoven fabrics*

Three sets of needlepunched nonwoven fabrics were prepared by blending the alkali treated jute and polypropylene (PP) fibres in defined weight proportions, i.e., 20, 40 and 60 wt.%. These fibres were opened and carded and subsequently, passed through a cross-lapper to form cross-laid webs. These cross-laid webs were then made to pass through the needlepunching process to prepare the nonwovens of nominal mass per unit area of 400 g/m^2. The process parameters (punch density of 150 cm^{-2}, depth of needle penetration of 12 mm) were kept constant during the fabrication of nonwoven samples. Subsequently, the mass per unit area, thickness, and tensile strength of jute/PP needlepunched nonwovens were determined, as shown in Table 2. The thickness of needlepunched nonwovens was determined at 2 kPa according to ASTM D5729 and the tensile test of nonwoven was carried out based on ASTM D4595. It should be noted that the majority of fibres in the nonwovens were preferentially aligned in the cross-machine direction. Hence, in this study, the cross-machine direction is considered to be preferential direction whereas the machine direction indicates non-preferential direction that has minimum number of aligned fibres.

TABLE 1. Physical and mechanical properties of polypropylene, untreated and alkali treated jute fibres

Types of fibre	Linear density (tex)	Diameter (µm)	Tensile strength (MPa)	Modulus (GPa)	Breaking Extension (%)
Untreated Jute	2.81±0.24	53.38±5.93	369±97	38.92±10.52	1.18±0.30
Alkali treated Jute	2.74±0.20	49.00±4.36	533±171	42.40±7.92	1.30±0.25
Polypropylene	0.66±0.01	25.24±0.04	548±66	1.30±0.30	30±4.43

TABLE 2. Physical and tensile properties of polypropylene and alkali treated jute fibres blended needlepunched nonwoven structures

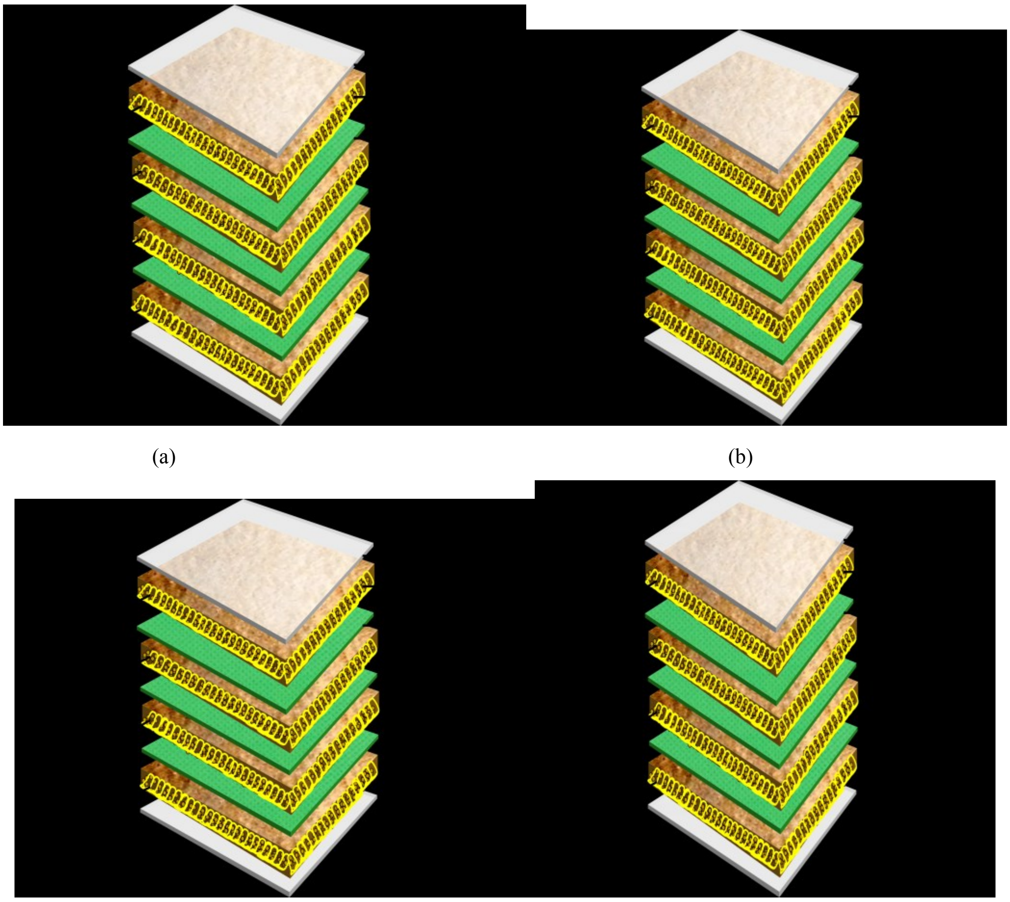
Wt. % of constituent fibres of Jute/PP blended nonwoven		Mass per unit area (g/m^2)	Thickness (mm)	Tensile strength in cross-machine direction (MPa)	Breaking extension in the cross-machine direction (%)	Tensile strength in machine direction (MPa)	Breaking extension in the machine direction (%)
Jute	PP						
20	80	412 ± 6.34	4.08±0.10	8.29±0.47	81.5±2.3	2.47±0.14	165.7±8.6
40	60	415 ± 4.85	3.71±0.08	8.45±0.51	77.9±3.7	2.18±0.11	170.8±7.1
60	40	388 ± 11.55	3.71±0.03	5.46±0.17	78.1±2.2	1.53±0.16	164.9±7.3

2.3 Fabrication of alkali treated jute/polypropylene blended needlepunched nonwoven reinforced composites

The pellets of polypropylene (PP) matrix was converted into films of 1 mm thickness at 190°C and a pressure of 50 bars was applied by a compression moulder (ERBA Press EKP 400) using picture frame moulds (dimensions of 250 × 220 × 1 mm^3). The PP films were then removed when the temperature dropped to 50-60°C and these films were stored in the laboratory at a room temperature. Jute/PP composites were then prepared by stacking PP films at the extremities covering the four layers of alkali treated jute/PP nonwovens having preferential and non-preferential directions and sandwiching three layers of PP spunbonded nonwovens, as shown in Fig. 1. Here, four layers of nonwovens consisting of preferential (cross-machine, X) and non-preferential (machine, M) directions were stacked in four distinct ways, i.e. MXMX, XMMX, MXXM and MMXX, as illustrated in Fig. 1. Nonwoven composites containing different weight percentages of jute fibres were prepared using the compression moulder by curing the materials at the temperature of 190°C under a constant pressure of 50 bars for 15 min. When the mould temperature dropped to 60°C, the composite samples of dimensions 250× 220 × 3 mm^3 were removed and the specimens were cut for various mechanical tests. The weight and volume fractions of jute fibres in the jute/PP composites are given in Table 3. It should be noted that 20, 40 and 60 wt.% of jute in nonwovens has yielded 11 wt.% (ranges between 10.88-11.36%), 23 wt.% (ranges between 20.88-24.98%) and 33 wt.% (ranges between 31.04-33.34%) in nonwoven composites. Accordingly, the sample IDs have been assigned by considering the effect of stacking and jute weight content in nonwoven composites. For example, sample ID, MXMX11J denotes the alternate stacking of nonwovens in the machine and cross-machine directions and having a jute content of 11 wt.%, similarly, MMXX33J consists of two consecutive layers of nonwovens in the machine and cross-machine directions having a jute content of 33 wt.% and so on.

2.4 Composite testing

The tensile and three-point bending tests of the composite samples were carried out using Instron Universal testing machine (4411 series) and Zwick Roell-Z010 Universal Testing machine based on ASTM D3039M and ASTM D790, respectively. Specimen dimensions used for the tensile and three-point bending tests were 250 × 25 × 3 mm and 75 × 13 × 3 mm, respectively. A cross-head speed of 2 mm/min was used in the tensile tests whereas the bending tests were performed at a speed of 2.8 mm/min. It should be noted that the edges of composite samples were smoothened by sand paper in order to avoid stress concentration during the tensile and bending tests.



(a) (b) (c) (d)

Fig. 1. Schematic illustration of composites having needlepunched nonwovens in stacking sequence of (a) MXMX, (b) XMMX, (c) MXXM and (d) MMXX. Here, M and X stands for the orientation of fibres in the machine and cross-machine directions, respectively.

TABLE 3. Jute fibre weight and volume fractions in nonwoven composites

Sample ID	Wt.% of constituent fibres of Jute/PP in blended nonwovens		Jute fibre wt.(%) in composites	Jute fibre volume fraction (%) in composites
	Jute	PP		
MXMX11J	20	80	10.88	6.81
MXMX23J	40	60	24.98	16.62
MXMX 3J	60	40	33.34	23.04
XMMX11J	20	80	11.24	7.05
XMMX23J	40	60	22.77	15.00
XMMX33J	60	40	33.11	22.86
MXXM11J	20	80	11.36	7.13
MXXM23J	40	60	20.88	13.64
MXXM33J	60	40	31.04	21.23
MMXX11J	20	80	11.29	7.08
MMXX23J	40	60	22.74	14.98
MMXX33J	60	40	33.23	22.96

3. RESULTS AND DISCUSSION

Jute fibres are complex heterogeneous lignocellulosic polymers composed of cellulose, hemicellulose and lignin. These fibres are hydrophilic in nature due to the presence of large number of hydroxyl groups and hence, they are incompatible with hydrophobic matrices including polypropylene. Alkali treatment of jute fibres eliminates the hydroxyl groups and improves the compatibility between jute fibre and PP matrix as well as reducing the hydrophilicity of the fibres [16]. A typical reaction between jute fibre and alkali (NaOH) is shown below.

$$\text{Cell–OH} + \text{NaOH} \rightarrow \text{Cell–O}^{-}\text{Na}^{+} + H_2O + \text{impurity}$$

The alkali treatment causes the removal of lignin and hemicellulose that leads to less dense and less rigid interfibrillar regions [21]. Hence, these fibrils can easily rearrange themselves during the application of tensile load resulting in better load sharing. The removal of non-cellulosic materials including lignin, hemi-cellulose and pectin results in the weight loss, reduction in fibre diameter and enhancement in tensile properties [22]. A comparison between the physical and mechanical properties of untreated and alkali treated jute fibres are shown in Table 1. Furthermore, the physical and mechanical properties of blended needlepunched nonwoven fabrics prepared from alkali treated jute and PP fibres are given in Table 2. It can be clearly seen that the tensile properties of blended needlepunched nonwovens are higher in the cross-machine direction than that of machine direction as the fibres are preferentially aligned in the cross-machine direction. A detailed discussion on the mechanical properties of alkali treated jute and PP blended nonwoven composites is given below.

3.1Mechanical properties of jute/PP needlepunched nonwoven reinforced composites

Tensile and Flexural properties

In general, increasing the jute content in nonwoven composites has increased the tensile strength and modulus as shown in Table 4. However, a layering sequence, MXXM having jute content of 23 wt.% has higher tensile strength corresponding to same stacking sequence having jute content of 33 wt.%. It is speculated that the decrease in the tensile strength at 33 wt.% jute fibre content due to the non-uniform stress transfer caused by fibre agglomeration [6, 7]. The chances of occurrence of fibre agglomeration is higher in MXXM as the layers of majority of fibres aligned in the cross-machine direction are combined together with extremities consisting of minimum proportion of fibres aligned in the machine direction. Hence, the presence of large proportion of jute fibre ends in composites causes crack initiation and hence, potential failure of composites at an early stage. Nevertheless, the nonwoven composite sample, i.e., MXMX has yielded maximum tensile modulus having jute proportions of 23 and 33 wt.% in comparison to the other layering sequences. In MXMX layering sequence, it is anticipated that the uniform and effective stress transfer takes place within the composite through the alternate layers of jute fibres aligned in the cross-machine (preferential) and machine directions (non-preferential) through polypropylene matrix. It is anticipated that the stress transfer is initiated in the jute fibres aligned in the cross-machine direction and subsequently, the stress is being transferred to the other layer containing lower proportion of jute fibres aligned in the machine direction which is again supported by higher proportion of jute fibres aligned in the cross-machine direction through polypropylene matrix. Hence, MXMX layering sequence provides the effective stress transfer through the alternate layers of preferentially aligned jute fibres and polypropylene matrix. In general, there is a continuous reduction in breaking elongation with the loading of jute fibre content, as shown in Table 4. Since, the jute fibres have low breaking elongation and increase in jute content proportionately reduces the breaking elongation of nonwoven composites. However, there is no clear trend for optimal layering sequence for tensile strength and breaking elongation of jute/PP nonwoven reinforced composites. Since, these composites contained the same number of jute blended nonwoven layers and these layers were subjected to the same level of deformation during tensile testing. It is anticipated that these layers in composites shared the total load in a similar way in all the four stacking sequence [23].

In flexural testing of composites, various types of deformations including tension, compression and shearing occurs simultaneously. One of the primary differences between flexural and tensile loadings is that the former creates a non-uniform stress distribution whereas the latter applies the load uniformly along the length of the sample. The effect of jute fibre content in nonwoven composites on flexural strength and modulus has shown in Table 4. Interestingly, the magnitude of flexural stiffness of MXMX containing jute proportions of 23 and 33 wt.% is higher in comparison to the other layering sequence. This is due to the fact that the upper and lower surfaces of the specimens were subjected to higher deformations than the mid-plane during the flexural testing [23]. In MXMX, one of the surface layers has jute fibres that were preferentially orientated in the cross-machine direction. Moreover, in MXMX composite sample, the centre layers also contained the jute fibres aligned in the cross-machine direction for avoiding the weak thick block [23].

TABLE 4: Mechanical properties of Jute/PP nonwoven composites

Sample ID	Tensile Strength (MPa)	Tensile Modulus (GPa)	Breaking Strain (%)	Flexural Strength (MPa)	Flexural Modulus (GPa)
MXMX11J	22.15±0.56	1.88±0.016	2.4±0.08	35.37±3.83	1.27±0.032
MXMX23J	25.56±0.45	2.31±0.008	2.2±0.09	47.64±2.73	1.97±0.083
MXMX33J	26.96±0.67	2.59±0.067	1.9±0.07	47.15±1.22	2.34±0.205
XMMX11J	22.41±0.57	1.87±0.114	2.3±0.14	42.04±3.94	1.37±0.075
XMMX 23J	23.37±0.37	1.99±0.121	2.2±0.22	43.68±1.55	1.68±0.059
XMMX33J	25.97±0.64	2.53±0.093	1.8±0.08	45.01±2.07	2.07±0.245
MXXM11J	21.01±0.45	1.81±0.100	2.2±0.19	40.18±2.36	1.40±0.104
MXXM 23J	26.28±0.40	2.26±0.033	1.9±0.10	46.49±1.91	1.93±0.016
MXXM 33J	24.64±0.95	2.35±0.042	1.9±0.29	42.77±4.97	1.82±0.131
MMXX11J	23.83±1.35	1.89±0.098	2.6±0.21	36.99±1.86	1.19±0.056
MMXX 23J	26.55±0.85	2.02±0.081	2.6±0.17	42.76±3.91	1.66±0.003
MMXX33J	27.47±0.46	2.31±0.114	2.1±0.13	46.06±5.45	1.94±0.218

4. CONCLUSIONS

In this research work, the jute/PP nonwoven reinforced composites have been successfully prepared using compression moulding technique by film stacking method. The surface of jute fibres have been modified using alkali treatment. In general, increasing the alkali treated jute fibre content in nonwoven composites has enhanced their tensile strength, tensile modulus, flexural strength, and flexural modulus. On the other hand, the breaking elongation of jute/PP nonwoven composites has reduced with an increase in the jute content. The effect of stacking sequence of nonwovens on the mechanical properties of jute/PP composites has also been analysed. It was found that altering the layers of nonwovens having preferential and non-preferential alignment of fibres, i.e. MXMX has yielded the maximum magnitudes of tensile and flexural moduli specifically for jute contents of 23 and 33 wt.%. However, the effect of layering sequence has no significant effect on tensile strength and breaking elongation. It is anticipated that this systematic study would be a first step towards the development of structural and high performance composites in a cost-effective way based on optimisation of both jute content and stacking sequence of nonwoven layers in composites.

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