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SHORT COMMUNICATION

Studies on the mechanical properties of woven jute fabric reinforced poly(L-lactic acid) composites

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Abstract Development of ecofriendly biocomposites to replace non-biodegradable synthetic fiber composites is the main objective of this study. To highlight the biocomposites as a perfect replacement, the plain woven jute fabric (WJF) reinforced poly(L-lactic acid) (PLLA) composites were prepared by the hot press molding method. The influence of woven structure and direction on the mechanical properties i.e. tensile, flexural and impact properties was investigated. The average tensile strength (TS), tensile modulus (TM), flexural strength (FS), flexural modulus (FM), and impact strength (IS) of untreated woven jute composite (in warp direction) were improved about 103%, 211%, 95.2%, 42.4% and 85.9%, respectively and strain at maximum tensile stress for composite samples was enhanced by 11.7%. It was also found that the strengths and modulus of composites in warp direction are higher than those in weft direction. WJF composites in warp and weft directions presented superior mechanical properties than non-woven jute fabric (NWJF) composites. Chemical treatment of jute fabric through benzoylation showed a positive effect on the properties of composites. Morphological studies by SEM demonstrated that better adhesion between the treated fabric and PLLA was achieved.

1. Introduction

Solid waste disposal has become a burning problem nowadays. Garbage wastes such as plastic grocery bags, food packaging materials, bottles, containers etc. are mainly responsible for causing environment pollution in urban areas due to non-biodegradable nature. At the same time, the emission of green house gases during combustion is a serious global-scale problem. To keep our environment safe and green, it is compulsory to reduce the use of such pollution causing garbage. That is why, many countries banned plastic grocery bags responsible for so called “White Pollution”. Alternative usage of

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biodegradable plastics and their natural fiber biocomposites gained more popularity because they are degraded easily after landfill. Therefore, it may lead to one of the solutions for the issue of disposal ground depletion.

Keeping this target, recent research efforts are being harnessed in developing a new class of fully biodegradable composites (biocomposites) by combining natural fiber with biodegradable polymer (Baghaei et al., 2013). A number of commercially available biodegradable polymers such as polyhydroxyalkanoate (PHA), poly(L-lactic acid) (PLLA), polycaprolactone (PCL), polyesteramide (PEA) etc. are used frequently as matrices of natural fiber composites. In the class of biodegradable polymers, PLLA has the greatest potential in the composite industries because of its facile availability, good biodegradability and high mechanical properties (Shukor et al., 2014). Though PLLA has superior properties to polyethyleneterephthalate (PET) in various applications, some drawbacks such as brittleness, inferior resistant on thermal deformation and lower water vapor barrier properties have limited its extensive use (Petersson et al., 2007). However, by incorporating natural fiber into the PLLA matrix can successfully improve the overall properties of composites.

Short natural fiber/PLA composites have been investigated by several studies (Oksman et al., 2003; Bax and Mussing, 2008; Sawpan et al., 2007; Ganster et al., 2006). The average tensile strength found was about 50 MPa using compression molding and the injection molding technique. Modulus of short fiber reinforced composites was also found to be lower. The long hemp fiber/PLA composites were studied by Graupner et al. (2009). Mechanical strengths of the composite were also not so improved. On the other hand, woven fabrics have received extensive study as reinforcements since they provide acceptable mechanical properties, simple processing and conformability for advanced structural applications (Jekabsons and Bystrom, 2002). Woven fabric composites recommend more balanced properties than unidirectional laminas. The weaving of the fiber gives an interlocking that increases strength higher than fiber–matrix binding strength. Since fibers are attached together tightly in woven fabrics, pull-out is quite impossible, consequently need more strength to breakdown the fabric reinforced composites (Lomov et al., 2006). Sapuan et al. (2006) investigated the mechanical properties of woven banana fiber reinforced with epoxy composites. The tensile stress was found greater in X-direction (warp) than Y-direction (weft). Weaving patterns such as plain, twill, satin, basket, leno etc. are crucial factor in determining the response of the composites (Pothen et al., 2006).

A number of reports on WJF composites have been found so far but none deals with the use of WJF as reinforcement in poly(L-lactic acid). In most cases jute fiber was used either in warp or weft direction for making hybrid woven fabric composites with synthetic polymer matrix (Khalil et al., 2011). Reinforcing 2D and 3D woven structures for natural fabric reinforced polymer composites were developed by Lomov et al. (2009). However, the properties of plain WJF reinforced polyester composites were found to have tremendous potential for improving the performance of composite structures due to longer stability, higher tensile, flexural, in-plane shear, interlaminar shear, impact properties and low manufacturing cost of plain woven fabric (Ahmed and Vijayarangan, 2007). Therefore, plain woven jute fabrics have been introduced in this study to fabricate composite by the compression molding technique. In order to get good adhesion between fiber and matrix (which give better mechanical strength in natural fiber/fabric reinforced composites) fibers have been modified chemically as like Lai and Mariatti, 2008. The effect of fiber orientation (warp and weft) on mechanical properties of woven fabric composites has also been reported.

2. Experimental

2.1. Materials

The PLLA polymer having an average molecular weight of 110,000 g mol^{-1} was synthesized in melt polycondensation methods (Khan et al., 2013). Unbalanced plain weave jute mat 52×44 (52 yarns in warp direction and 44 yarns in weft direction per 100 mm), having an average weight 200 g m^{-2} and average thickness of 6 mm was collected from Fatima-Alyaf Tala-e Jute Industries Ltd. Gazipur, Bangladesh (Fig. 1). Raw jute (unidirectional mat) was collected from local market of Jhenidha, Bangladesh.

2.2. Molding of woven and nonwoven fabric composites

Composite fabrication process was completed in two steps. In the first step PLLA films approximately 0.2–0.3 mm in thickness were prepared by 2 polished stainless steel (SS) sheets in a hot press molding machine. Molding machine is accomplished by hydrolic press and hot plate. Molding temperature and pressure can be as high as 250 °C and 250KN, respectively. SS sheets were kept for 10 min at 180 °C and 50KN pressure thereafter it was cooled by tap water. For the second step, square WJF of $(15 \times 15)\ \text{cm}^2$ in dimensions were cut and dried in an oven at 60 °C for 24 h to remove moisture. The prepared PLLA films were also cut into the same dimension like fabric. A rectangular stainless steel (SS) mold with 15×15-cm square cavity and 10 mm depth was used for composite fabrication. The mold was packed by WJF in between the

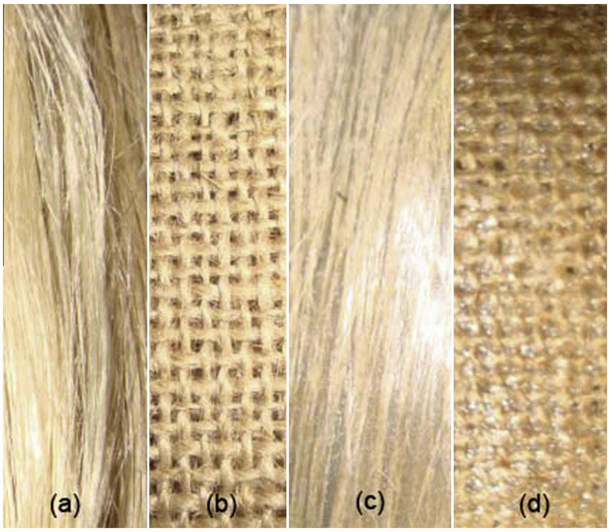

Figure 1 Image of (a) unidirectional jute, (b) plain woven jute fabric, (c) nonwoven jute fabric composite and (d) plain woven jute fabric composite.

PLLA films maintaining fixed weight fraction of woven fabric in composite. A mold releasing spray (BONEY-Mould release silicon spray, manufacturer-London chemicals Ind. England) was used for easy opening the mold. The mold was then placed on a hot press molding machine and composite was fabricated as like PLLA film making. Same procedure was followed for NWJF/PLLA composites, where fibers were placed unidirectionally. Weight fractions of fabrics in composites were calculated by the following formula:

$$W_f = \frac{W_j}{W_m + W_j}$$

where W_f, W_j, and W_m are the weight fractions of fabric in composite, weight of jute fabric and weight of polymer matrix respectively.

2.3. Mechanical measurements

Tensile test was conducted in both warp and weft directions according to ASTM D882 (E) using a Universal Testing Machine (Hounsfield UTM 10KN). The specimens for tensile were cut in 30 mm wide dumbbell shape with an overall length of 110 mm and a 50 mm length of the narrow, 10 mm wide parallel-sided section. The dimension of clamped area between two clips was 40 mm × 15 mm × 0.5–1.0 mm. Test speed was fixed 2 mm/min. The yield stress, stain and modulus were measured by QMAT Pro for Textile Software Package.

Three-point flexural tests of composites were carried out using same Hounsfield UTM 10KN attached with computer program (QMAT Pro for Textile Software Package) according to the standard method used for flexural properties (ASTM D790–98). The specimens for tensile were cut into the dimensions: 79 mm × 10 mm × 0.5–1.0 mm. Test speed was fixed at 2 mm/min.

Notched Charpy impact tests (according to ASTM D6110–97) were carried out using a universal impact tester. A rectangular piece of sample was prepared according to Fig. 2. The specimen is having a V-notch at a point equidistant from the ends of the long side. All the results were taken as the average value of 10 samples. Unreinforced PLLA sample was also tested for comparison purpose.

2.4. Scanning electron microscopy

The tensile fractured surface morphology of composites was examined by scanning electron microscope (Philips XL-30). The instrument was operated with an accelerating voltage 30 kv. The samples were coated with 3 nm gold layer using a vacuum sputter coater.

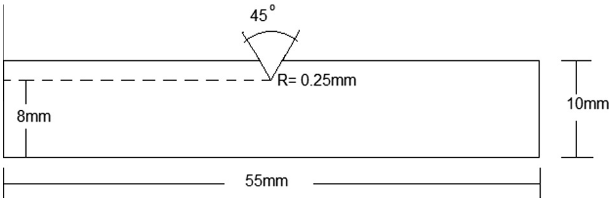

Figure 2 Simple beam notch Charpy impact test specimen.

3. Results and discussion

Figs. 3 and 4 represent the tensile stress–strain diagrams of unreinforced PLLA, untreated and treated WJF/PLLA composites in warp and weft direction, respectively. The initial portion of the curve of untreated WJF/PLLA composites is linear at low strain rates followed by a change in the slope of the curve indicating nonlinear behavior of the material. The start of nonlinearity in the curve is an indication of the initial matrix cracking followed by progressive failure of the fibers. TM was determined by the slope of the initial portion of stress–strain curve. A significant improvement in the TS and TM of PLLA was obtained by the reinforcement with untreated WJF; in warp direction their respective values were increased to 102.5% and 211.1%. In weft direction, TS and TM were also found to be 77.5% and 105.6% higher than unreinforced PLLA samples, respectively. The strains at maximum tensile stress for untreated WJF/PLLA composite samples were found to be 3.8% in warp direction and 4.1% in weft direction. It has been noticed that TS, TM and elongation properties of untreated WJF/PLLA composite are higher in warp direction than weft direction.

When tensile stress is applied on woven fabric composite, it induces transverse loads at fiber overlap sections of crimped fibers which attempt to straighten. This reduces the translation of fiber strength to fabric strength and decreases long-term fatigue and creep rupture performance (McDaniels et al., 2009). However, these kinds of crimp effects depend on fabric density of composite. The WJF contains more number of fibers in warp direction than in weft direction. Due to its higher yarn at warp direction composite having lower density might be the reason why its performance shows contrast with weft direction of composite. The orientation of yarns in fabric also resulted in the difference of tensile strain value. In a single layer warp woven composites, the longer yarns can extend more during the tensile test. For this reason, tensile stain is found greater in warp direction.

The flexural modulus is a measure of the resistance to deformation of the composite in bending. The flexural behavior of jute fabric composites is presented in Figs. 5 and 6. Under the flexural loading, the surfaces of the specimen

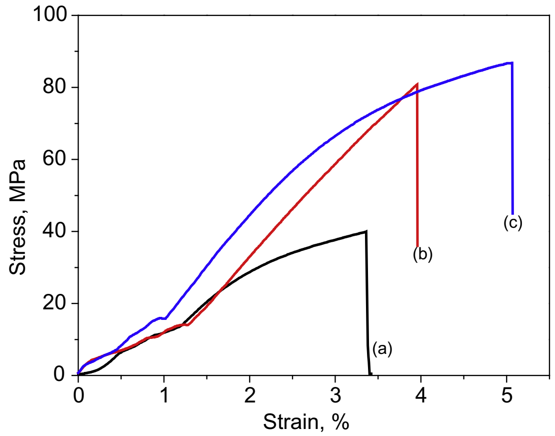

Figure 3 Tensile stress–strain diagrams of (a) PLLA, (b) untreated WJF/PLLA composite in warp direction and (c) treated WJF/PLLA composite in warp direction.

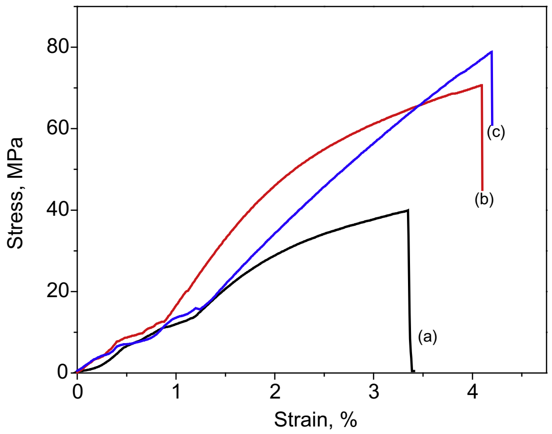

Figure 4 Tensile stress–strain diagrams of (a) PLLA, (b) untreated WJF/PLLA composite in weft direction and (c) treated WJF/PLLA composite in weft direction.

are subjected to greater strains than the sample center. Hence, FS and FM are controlled by the strength of the extreme layers of reinforcement (Munikenche et al., 1999). Composites faced compressive and tensile fracture during flexural test. Surface layer of composites faced compressive fracture while the tensile mode on the bottom layer. The average FS and FM of untreated WJF/PLLA composite in warp direction were found to be 95.2% and 42.4% higher than the unreinforced PLLA. As like tensile properties, flexural behavior of WJF/PLLA ric composite is found higher in case of warp direction than weft direction. Short yarns in weft direction of composite limit their tensile stress dispersion. Therefore, as the tensile stress tries to propagate upwards, delamination failure occurred thus reducing its flexural strength (Wong et al., 2010).

The effect of WJF on impact strength of PLLA is presented in Table 1. The average impact strength of untreated WJF/PLLA composite in warp direction (16.4 kJ/m^2) is 85.9% higher than the impact strength of unreinforced PLLA. This indicates that woven fabric plays an important role in the impact resistance of the composite as they interact with the crack formation in the matrix and act as stress-transferring medium. Containing higher aligned fibers at warp direction, the composite produced higher resistance to impact stress.

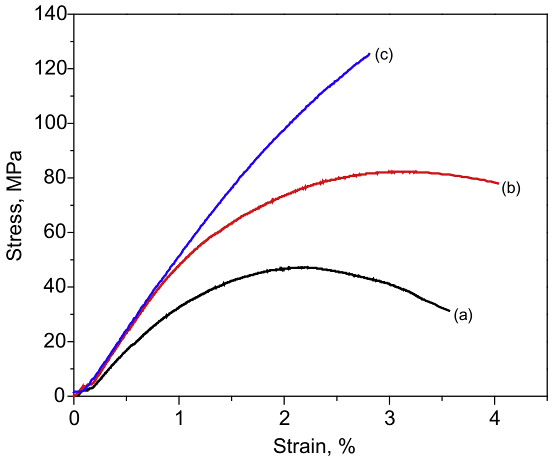

Figure 5 Flexural stress–strain diagrams of (a) PLLA, (b) untreated WJF/PLLA composite in warp direction and (c) treated WJF/PLLA composite in warp direction.

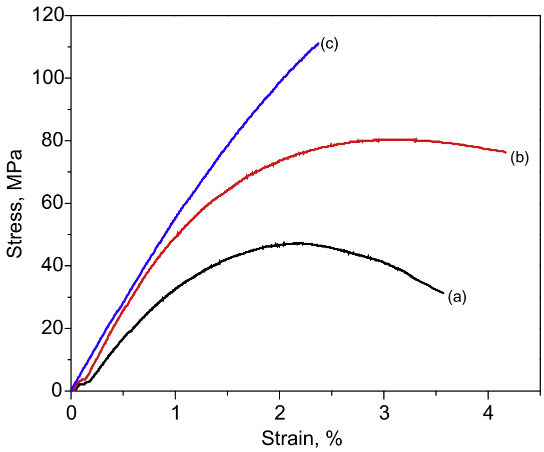

Figure 6 Flexural stress–strain diagrams of (a) PLLA, (b) untreated WJF/PLLA composite in weft direction and (c) treated WJF/PLLA composite in weft direction.

It is also seen that the mechanical properties of WJF/PLLA composites are higher than those of NWJF/PLLA composites (Table 1). In woven fabric, fiber yarns of warp direction crossover under the fiber yarns of weft direction to create an interlocking structure. Under tensile loading, these crimped fibers tend to straighten out, which create high stresses in the matrix. As a result, the strength of the woven fabric composite is greater than the strength in NWJF/PLLA composite.

Figs. 3–6 and Table 1 show that benzoylated woven jute reinforced PLLA composites possessed higher TS, TM, FS, FM and IS compared with those of untreated counterparts. It indicates that the composites possess better interfacial bonding due to fiber surface treatments. Untreated woven jute reinforced PLLA, which had poor interfacial bonding between the fabric and the matrix, showed a lower tensile strength due to the fact that a lower load is needed to break and pull-out the fiber from the matrix (Fig. 7). However, the poor interfacial bonding property between the fabric and the matrix made it easier for the fiber to debond from the matrix. The crack was somewhat blunt and the composites showed brittle properties. For treated woven jute reinforced PLLA composites, due to the improved interfacial bonding properties, the pull-out fiber from the matrix is rare and a good fracture resistance property was achieved.

4. Conclusion

In the present research effort, mechanical tests were conducted on woven and non-woven jute fabric reinforced PLLA based composites. Based on the experimental results, the following conclusions can be drawn:

(i) Woven structure exhibited excellent mechanical behavior under tensile, flexural, and impact loadings compared to non-woven composite.
(ii) Tensile, flexural, and impact strengths of WJF/PLLA composite were found higher at warp direction than weft direction.

Table 1 Mechanical properties of jute fabrics/PLLA composites.

Sample	Tensile strength (MPa)	Tensile modulus (GPa)	Strain (%)	Flexural strength (MPa)	Flexural modulus (GPa)	Impact strength (kJ/m^2)
Unreinforced PLLA	40 ± 6.3	0.36 ± 0.001	3.4	42 ± 9.7	3.02 ± 0.8	8.82 ± 0.9
NWJF/PLLA composite	55 ± 11.5	0.867 ± 0.02	6.01	67 ± 8.4	2.83 ± 1.1	12.98 ± 1.1
At warp direction						
Untreated WJF/PLLA composite	81 ± 13.5	1.12 ± 0.034	3.8	82 ± 12.0	4.3 ± 0.10	16.4 ± 1.8
Treated WJF/PLLA	87 ± 8.5	1.42 ± 0.047	5.1	121 ± 13.4	5.3 ± 0.10	18.1 ± 2.3
At weft direction						
Untreated WJF/PLLA composite	71 ± 8.7	0.78 ± 0.063	4.1	81 ± 9.4	3.62 ± 0.08	14.3 ± 1.5
Treated WJF/PLLA composite	79.2 ± 9	0.91 ± 0.057	4.2	111 ± 8.1	4.72 ± 0.05	16.6 ± 1.8

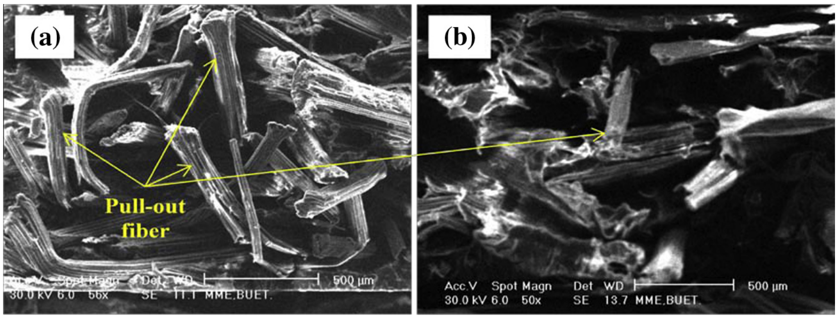

Figure 7 Scanning electron micrographs of tensile fracture surface of (a) untreated WJF/PLLA composite in warp direction and (b) treated WJF/PLLA composite in warp direction.

(iii) Chemically modified WJF/PLLA composite offered better strength and modulus than untreated WJF/PLLA composites.

Finally, it can be concluded that PLLA based woven jute fabric composites might be a good alternate of synthetic fiber composites and are suitable for high load bearing applications. Further investigations have to be carried out to determine the thermal and biodegradability of these composites.

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