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Mechanical characterization of animal fibre-based composites

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Horsehair-based composites have been prepared by reinforcing polylactic acid (PLA) using hot compression molding. The weight fraction of horsehair fibre in composites has been varied from 0% to 30 wt.% to investigate the effect of fibre loading on the mechanical properties and moisture absorption performance of the developed composites. The mechanical properties, such as strength and modulus (tensile and flexural), impact energy, and moisture absorption behaviour of the fabricated composites, are experimentally evaluated. The experimental results recommend that the composites reinforced with 20 wt.% horsehair exhibit superior mechanical properties as compared to other developed composites. The tensile strength and modulus, flexural strength and modulus, Charpy and Izod impact energy of the composites reinforced with 20 wt.% horsehair are improved by 9.52, 28.74, 7, 5.63, 398.11 and 379.31% as compared to, one-on-one, neat PLA. The findings also reveal that the percentage of moisture absorption of the developed composites increases with an increase in the fibre content in the developed composites.

Keywords: Animal fibre, Composites, Mechanical properties, Moisture absorption, Polylactic acid

1 Introduction

The natural fibre (plant, animal, mineral, etc.) based composites are emerging at a faster rate due to their various advantages over synthesis fibre (glass, carbon, aramid, etc.) based composites. Plant fibres, such as jute, sisal and bamboo are widely used for the development of natural fibre-based composites[1-3]. However, research on the development of animal fibre-based composites is relatively not much available in comparison to plant fibre-based composites. Thus, the attention of various researchers has shifted towards the development of animal fibre-based composites as these light-weight fibres are easily available in low-cost and possess high specific strength[4,5]. Human and animal hairs are generally treated as waste materials and disposed of to environment. But disposal of these materials through burning and burying causes environmental pollution. The recent studies showed that the utilization of these waste for the development of composites can effectively solve the disposal problem[6-8]. The properties (physical, chemical and mechanical) of animal hair depend on the various factors like location of hair, age of the animal, and type of animal[9]. In present times, natural fibre-based composites are extensively used in automobile, building, and furniture applications[10]. The primary aim of developing this type of bio-based composites is their sustainability and biodegradability characteristics. Polylactic acid (PLA) is a fully biodegradable polymer which is derived through treatments of sugar beet, corn, potato, and other agriculture-based materials[11,12]. PLA has excellent mechanical properties and can easily be processed for many applications. However, PLA has some limitations such as high brittleness, low impact strength, and water sensitivity[13]. Plant fibre-based composites degrade at a faster rate than the animal fibre-based composites when exposed to soil. This indicates that the mechanical behaviors of animal fibre-based composites are better than the plant fibre-based composites[14]. The various factors affecting the natural fibre-based composites are the geometry of fibre, content of fibre, and orientation of fibre. The loading of fibre is an important parameter as it significantly affects the strength of a composite[15,16]. The influence of fibre loading on the tensile and flexural properties was studied[17]. It was concluded that these properties of the composite are improved with an increase in the fibre loading to a certain extent and then degrades with further increase in the fibre loading. The effect of fibre orientation was also studied and it was found that the parallel orientation of fibre results in

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improved mechanical properties as the fibres are aligned parallel to the direction of the applied load[18]. In this work, mechanical properties and moisture absorption performance of the horsehair fibre-based PLA (HH/PLA) composites have been evaluated. Four different types of composites are fabricated by varying the fibre lading (0, 10, 20, and 30 wt.%) using hot compression molding.

2 Materials and Methods

2.1 Materials

Horsehair as reinforcement was used for fabricating the composites as it is easily available at a nominal cost, biodegradable, and waste material. Golden brown horsehair were collected from local horse shed near Patna, India. The length and diameter of the horsehair were approximately 15 cm and 0.18 mm respectively and the shape was almost cylindrical. Collected horsehairs were cleaned and washed several times using tap water to remove the impurities and dried with the help of hair dryer. Washed and cleaned hairs were arranged in longitudinal directions for making mats with the help of yarn. These mats were then pressurized at normal temperature and pressure to obtain uniform thickness throughout the mat. These mats were used for the fabrication of composites. Polylactic acid (PLA) was used as matrix material which was procured from Nature Tec. India Pvt. Ltd, Chennai, India. Some properties of PLA are given below:

Property		Value
Chemical formula	:	$(C_3H_4O_2)_n$
Density	:	1.25 g/cm^3
Glass transition temperature	:	55-60˚C
Melting point	:	150-160˚C
Relative viscosity	:	3.3

2.2 Fabrication of Composites

Composite sheets were fabricated by compression molding (Make: Hind Hydraulics & Engineering) applying film-stacking method. In this method, PLA granules were first converted into a thin sheet using compression molding machine at a temperature close to its melting temperature and desired pressure. The unidirectional horsehair mat was placed in between the PLA sheets. A total five layers of horsehair mats and polymer sheets were incorporated to achieve the composite thickness of 5 mm by trial and error method. The three layers of PLA sheets and two layers of horsehair mats were alternatively arranged. The horsehair mats were placed in between the PLA sheets. Then the temperature and pressure were applied for consolidation purpose. The mold was kept under pressure and then the consolidated composite sheet was removed from the mold as shown in Fig.1. The specimens were cut from the fabricated composite sheet for tensile, flexural, impact, and moisture absorption testing as per ASTM standards. Four types of samples were prepared having different fibre loadings of 0, 10, 20, and 30%. The measured densities of the developed composites having fibre loading of 0, 10, 20, and 30% are found 1.2765, 0.8534, 0.8039, and 0.7736 g/cm^3. The different processes parameters involved during the fabrication of composites are given below:

2.3 Mechanical Testing

Universal testing machine (Zwick/RoellZ250) was used to perform both tensile and flexural tests. The tensile test was conducted as per ASTM standard D3039M-14. ASTM D790 standard was followed to find the flexural properties of the developed composites. Three samples of each composite configuration were considered for both tests and the

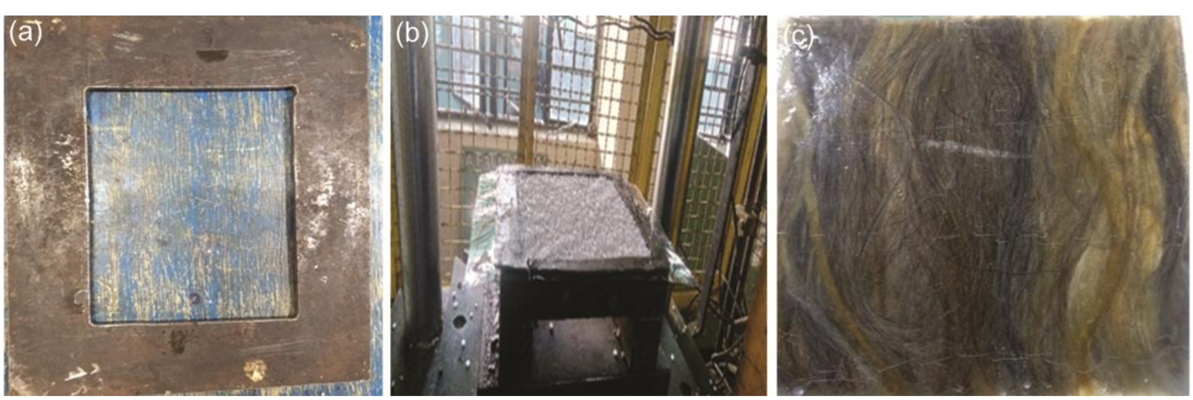

Fig. 1 — Fabrication of composites sheets (a) mold used for fabrication, (b) processing of PLA granules, and (c) fabricated composites sheet

average value was reported. Impact tests were conducted as per ASTM D256 (Izod Impact Test) and ASTM A370 (Charpy Impact Test) using impact tester. The notched specimens were used for both types of impact tests[19]. All the mechanical testing was performed at atmospheric temperature and pressure. The moisture absorption test was performed as per ASTM D570-98. For the moisture absorption test, the prepared samples were soaked in water and then the weight gain of the sample was measured at a regular interval until the moisture absorption attains the saturation point.

Property		Value
Pressure	:	100 kg/cm²
Load applied	:	28 ton
Upper mold temperature	:	100-180°C
Lower mold temperature	:	90 to 170°C
Volume of mould	:	16.5 cm × 14 cm × 0.5 cm
Heating rate	:	1.67°C/min
Cooling rate	:	1.4°C/min

3 Results and Discussion

3.1 Effect of Fibre Loading on Tensile Properties

The variation in strength and modulus of each specimen with different fibreloading is shown in Fig. 2. Both strength and modulus increase with an increase in fibre weight percentage from 0% to 20%. The maximum tensile strength (30.33 MPa) and modulus (4.52 GPa) are found for HH/PLA composites consisting of 20 wt.% horsehair which is 9.52% and 28.74% higher than the neat PLA and 56.19% and 106.46% higher than composites reinforced with 30 wt.% horsehair. This indicates that the mechanical interlocking between PLA and horsehair is adequate to transfer the load from PLA to horsehair and the effect of reinforcement (horsehair) is predominant for HH/PLA composites loaded with 20 wt.% horsehair. A low load transfer capacity which leads to the failure of the developed composites is seen when fibre loading is increased to 30 wt.%. The interfacial bonding area increases with the fibre loading which results in poor bonding between the polymer (hydrophobic) and the fibre (hydrophilic). Thus, the tensile properties of the developed composites are reduced as fibre loading is reached beyond 20 wt.%. The similar behavior of the tensile properties is observed with varying fibre loading [20,21]. The polymer may not make bonding with all the fibres at higher fibre loading of composites. Thus, the stress transfer between horsehair and PLA is not adequate. Hence, the strength and modulus of the developed composites are decreased. The strength of the composite is also affected by other factors such as bonding characteristic, fibre length, etc.[22]

3.2 Effect of Fibre Loading on Flexural Properties

The composites specimens with varying content of horsehair (0-30 wt.%) are considered for flexural testing. The variation of flexural strength and modulus of the different composite samples are illustrated in Fig. 3. The flexural strength and modulus have a similar trend to that of tensile strength and modulus with varying fibre loading from 0 wt.% to 30 wt.%. The flexural strength and modulus are found to be maximum for HH/PLA composites reinforced with 20 wt.% horsehair. These values are 66.72 MPa and 20.24 GPa which are 7% and 5.63% higher than the neat PLA and 99.56% and 141.94% higher than the composites reinforced with 30 wt.% horsehair. This indicates that 20 wt.% horsehair and 80 wt.% PLA make excellent bonding. Thus, both the constituents of composites can effectively transfer the stress that generates due to the applied load. Both flexural strength and modulus decrease as the weight percentage of horsehair is further increased, which is plausibly due to the inadequate bonding between the fibre and the polymer. The similar observation is also reported earlier[23,24].

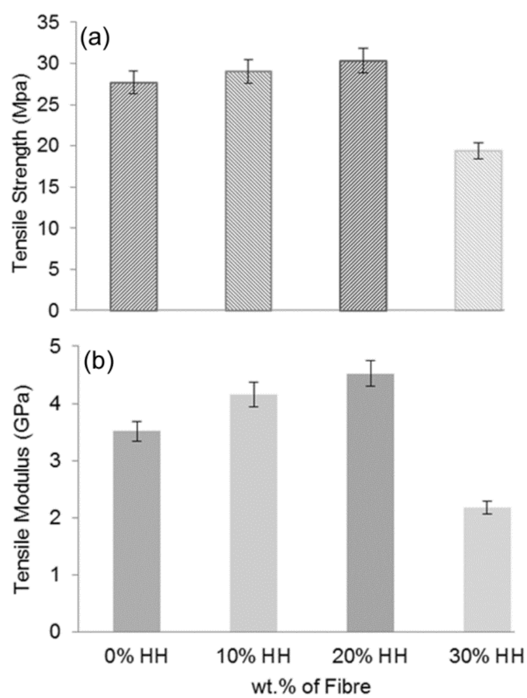

Fig. 2 — (a) Tensile strength *vs*. fibre loading and (b) tensile modulus *vs*. fibre loading

3.3 Effect of Fibre Loading on Impact Properties

Impact resistance is the ability of the material to resist breakage under shock loading or stress applied at high speed. Both the Charpy and Izod methods are applied to study the impact behavior of the developed HH/PLA composites. The variation of Charpy and Izod impact energy with respect to fibre loading is shown in Fig. 4. It is evident from the figures that the impact strength increases as the fibre loading increases from 0 wt.% to 20 wt.%. This corroborates the findings of the earlier work[25,26]. The figures also indicate that the impact energy of the developed composite decreases as the fibre loading is reached beyond 20 wt.%. This is due to the increase in size of the poor bonded area between horsehair and PLA with the fibre loading. The maximum impact energy obtained in both Charpy (5.28 J) and Izod (2.78 J) tests for the composites reinforced with 20 wt.% horsehair are 398.11% and 379.31% higher than the neat PLA and 109.52 % and 118.89 % higher than the composites reinforced with 30 wt.% horsehair.

3.4 Effect of Fibre Loading on Moisture Absorption

The moisture absorption test is performed for each type of developed composites. In this test, the composite sample is first dried using an oven at 60˚C for 12 h. Then the test sample is cooled and weighed immediately using a weighing machine (accuracy: 0.001g). All test samples are soaked in water for 24 h. The samples are taken out of the water at a regular time interval. The excess water present on the surface of the test sample is wiped using cloth before weighing the sample. The same process is repeated until the moisture absorption reaches its saturation. The percentage of moisture absorption is calculated using the following equation:

$$\text{Moisture absorption (\%)} = \frac{w_2 - w_1}{w_1} \times 100 \quad \ldots (1)$$

where w_1 and w_2 are the weight of the test specimen before and after moisture absorption respectively.

The moisture absorption behaviour of HH/PLA composites as a function of fibre loading is shown in Fig. 5. The percentage of moisture absorption is indicated with a time interval of 24 h for all samples. The figure simply indicates that the percentage of moisture absorption of HH/PLA composites increases as the weight percentage of horsehair is increased from 0 wt.% to 30 wt.%. The figure also represents that the HH/PLA composites reinforced with 30 wt.% horsehair is quite high as compared to the other

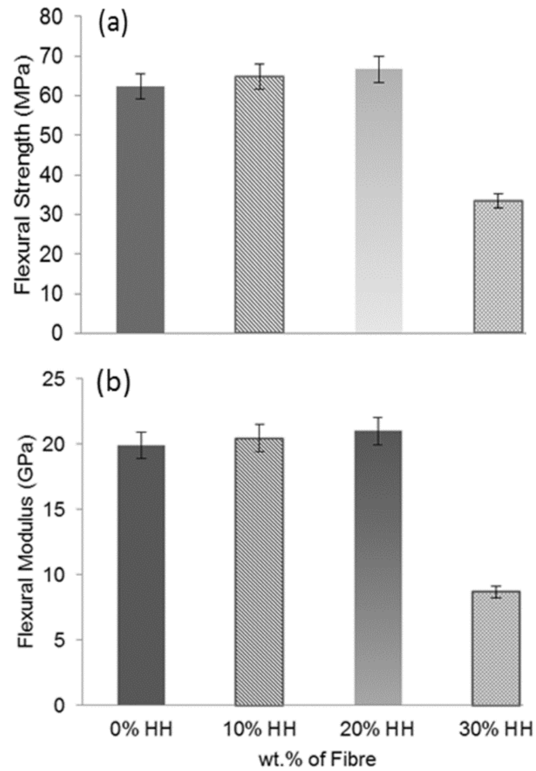

Fig. 3 — (a) Flexural strength *vs.* fibre loading and (b) flexural modulus *vs.* fibre loading

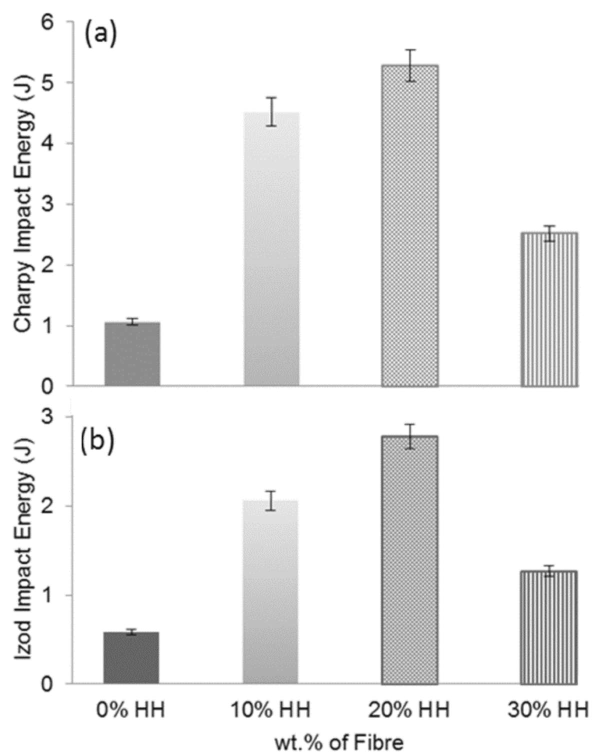

Fig. 4 — (a) Charpy impact energy *vs.* fibre loading and (b) Izod impact energy *vs.* fibre loading

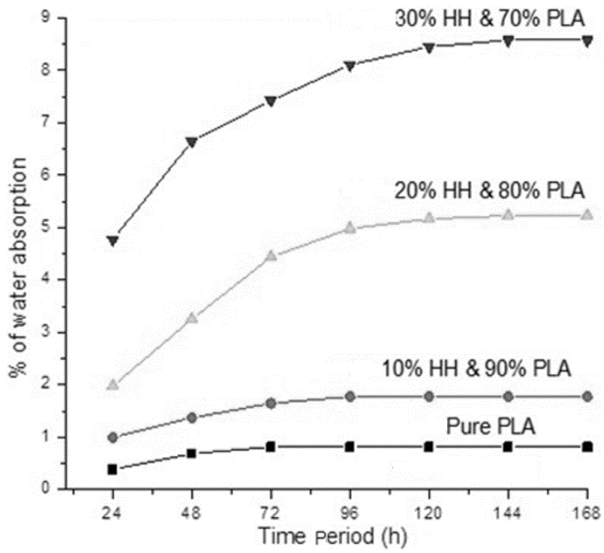

Fig. 5 — Effect of fibre loading on the moisture absorption

developed composites. This poor bonding between the fibre and polymer results in more micro-voids in the composites. This leads to increased moisture absorption as moisture is easily absorbed by these voids. However, the percentage of moisture absorption is negligible for neat PLA as compared to its composites.

4 Conclusion

The major findings from the present experimental study on mechanical and moisture absorption performance of HH/PLA composites are summarized below:

4.1 Both tensile strength and modulus increase as the fibre loading in the composites is increased from 0 wt.% to 20 wt.%. HH/PLA composites fabricated with 20 wt.% horsehair show maximum strength and modulus as compared to the other composites.

4.2 The flexural strength and modulus show a similar trend of tensile strength and modulus with the variation in fibre loading.

4.3 The maximum impact energy is obtained with HH/PLA composites fabricated with 20 wt.% horsehair in both Charpy and Izod impact tests.

4.4 The moisture absorption tendency of the developed HH/PLA composites increases linearly with the fibre loading.

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