Influence of Yarn Hairiness on the Mechanical Properties of Unidirectional Jute Polyester Composites

Ranajit K Nag*, Michael J Clifford, and Andrew C Long

***Abstract*—Tossa jute yarn as received from the supplier is denoted as "hairy yarn" and after removing hairs, yarn is denoted as "hairless yarn". Hairs are removed manually by burning using a candle flame. Tensile properties of hairy and hairless yarn are measured. Differential scanning calorimetry, X-ray photoelectron spectroscopy and fourier transform infrared analysis are performed to understand the difference in properties between hairy and hairless yarns. Unidirectional (UD) mat of "unsized yarn" is prepared by wrapping it on a metal frame and UD mat of "sized yarn" is prepared by wrapping it on a drum and applying hydroxyethyl cellulose solution (a water based adhesive) as binder. Unidirectional composites are manufactured using hairy and hairless yarns separately. Unsaturated polyester resin is used as matrix and composites are manufactured via resin transfer moulding. Composites test results show an increase in tensile modulus (5.5%) and decrease in strain at failure (7.5%) of composites manufactured with unsized hairy yarn compared to those manufactured with unsized hairless yarn in the longitudinal direction. Composites manufactured with unsized hairy yarn shows an increase in strain at failure (86%) compared to that of composites manufactured with unsized hairless yarn in transverse direction.**

***Index Terms*—Composites, hair, unidirectional, yarn**

I. Introduction

'Hairiness is a property which indicates the amount and length of fibre ends and loops protruding from the body of the yarn' [1]. Hairiness is an inherent character of a spun yarn composed of staple fibres and is considered as a fault in textiles. Hairiness is undesirable for most textiles, but is desirable for certain types of cloths (such as flannel, soft knitwear and towel). Thus yarn with low hairiness is a common demand. Yarn hairiness influences fabric pilling, handle, comfort and appearance [2].

As a protruding fibre from the yarn surface, one end of the hair is embedded and twisted into the yarn body and the other end (which is open) is known as the hair. Most of the hairs are affixed strongly to the yarn. Hairs can be wetted easily by resin during infusion and bonding between hairs and resin may influence the interfacial properties of composites. Thus mechanical properties of composites manufactured with hairy yarn may be different from those of composites manufactured with hairless yarn. To investigate the influence of hairiness on the mechanical properties of composites, hairy and hairless yarns used to fabricate composites are studied in this paper.

A staple yarn consists of 60−200 fibres in cross-section [3−4] and a small number of these fibres may contribute to hairs. Thus the influence of hairiness on the mechanical properties of composites may not be significant in the longitudinal direction of yarn. However, the influence of hairiness may be more pronounced in the transverse direction of the yarn. Tensile tests of composites are performed in the longitudinal as well as the transverse direction to assess this.

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II. Materials and Methods

A. Materials

Tossa jute yarn is used as reinforcement material in this experimental work, supplied by Janata Jute Mills Ltd. Bangladesh. This is a single ply jute yarn having 8 lbs/spyndle (280 Tex, 1 lbs/spyndle = 35.090 Tex) linear density and 4.65 twist per inch. The yarn is supplied in spool form and no extra finishes or coatings are used except the emulsion applied during spinning that contains jute batching oil. Unsaturated polyester (UP), trade name POLYLITE® 420-100 by Reichhold UK Ltd. is used as the matrix material. Methyl ethyl ketone peroxide 35% in phthalate plasticizer, trade name Butanox Catalyst by K & C Mouldings (England) Ltd., is used as catalyst and cobalt (11) (2-ethylhexanoate) 1% CO in diisobutyl phthalate, trade name Accelerator NL-40P by K & C Mouldings (England) Ltd., is used as accelerator. The mould release agent is Chem lease® PMR-90 manufactured by Chem-Trend (Deutschland) GmbH. Hydroxyethyl cellulose (HEC) from Dow Europe GmbH, commercial name Cellosize HEC QP-52000H, is used as binding material for the Unidirectional (UD) fibrous mat of yarn.

B. Preparation of Yarn

As hairs are considered as a fault, several techniques are practised to reduce or remove hairs. Yarn hairiness decreases with increasing twist per unit length [5, 6]. However, increase in twist has a number of detrimental effects such as increasing the cost of yarn, bringing higher fibre obliquity as well as misalignment of fibres to the axis of the yarn, increasing yarn crimp in woven fabric and hindering penetration of resin during composite manufacturing [7]. Thus this is not a suitable way to reduce hairiness. Some established methods are practised to remove hairs in textiles processing. A popular method of removing hairs is burning [8]. Burning can be performed using a flame [9] or using hot plate(s) or hot roller(s) [10]. Hairs can also be removed by enzyme treatment [11].

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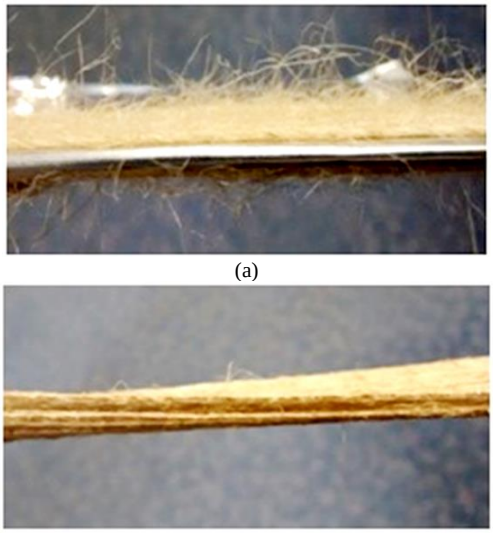
In this work yarn hairs are removed by burning, performed manually using a candle flame. This task is performed carefully to avoid any damage to the yarn.



(a)

(b)

Fig. 1. Unsized hairy yarn (a) and HEC sized hairy yarn (b) wrapped on board.

To produce composite plaques of sized yarn, both hairy and hairless yarns are wound on a motor operated drum separately to get UD yarn mat. The drum speed is set at 25 revolutions per minute and the drum diameter is 32 cm. A fixed position yarn guide is used to facilitate winding and the winding drum gives traverse motion. The drum rotation and traversing speed are adjusted to wind yarns on the drum close together avoiding gaps or overlapping. Care is taken to avoid slackness or stretching of yarns during winding.

Tap water is used to make 0.6% (by weight) HEC solution. A homogenous solution is produced with the help of a mechanical stirrer. Stirring is performed for 10 minutes at 200 revolutions per minute. This solution is applied by hand to the yarns wrapped on the drum using a brush. Yarns are dried in an oven at 105 ºC [12] on the drum for one hour. After drying, yarns are allowed to cool and are removed from the drum surface by cutting. These yarns are stored at ambient condition for at least 48 h before use for composites manufacturing. Application of the binding agent is undertaken to produce the UD mat. The areal density of the UD mat is 400–500 g/m^2. The binding agent take-up is measured as 1.5−1.8% (by weight) of the yarn.

HEC forms a film around the yarn that flattens the hairs, resulting in a comparatively smooth yarn surface (Fig. 1 (a) and (b)). Hence the influence of hairiness on the mechanical properties of composites might not be as prominent for composite plaques manufactured with HEC sized hairy yarn and so composite plaques were also manufactured with unsized hairy and hairless yarn.

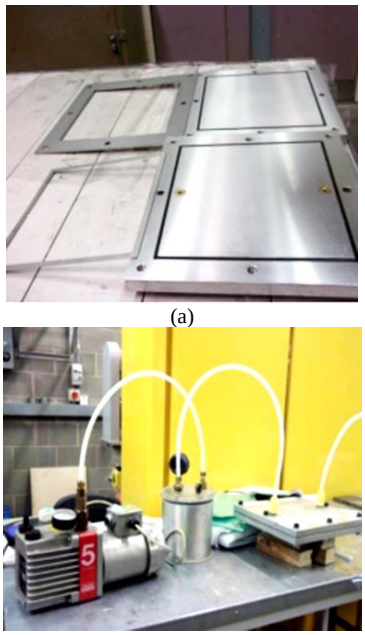
TABLE I: PROPERTIES OF UNSATURATED POLYESTER (UP) RESIN BY RIECHHOLD NORPOL

Viscosity (mPas) (mins)	Gel time	Tensile modulus	Tensile strength	Failure strain
	at 25ºC	E_m (GPa)	σ_m (MPa)	%
210	30	3.7	70	3.5

An UD mats of unsized yarns were produced by wrapping yarn on a square steel frame. The dimensions of the frame are 260 × 260 × 1 mm. The width of the arms of the frame is 10 mm and yarns were wrapped on it closely together. Care was taken to avoid under-tension to minimize slackness and over-tension to avoid stretching of yarns. This frame including the yarn wound on it was infused to manufacture composites and the frame was removed after curing.

III. MANUFACTURING OF COMPOSITES

(260×260 mm) picture frame was used to infuse yarn. Yarn weight was noted before infusion to calculate the fibre volume fraction. The technical data of the matrix is presented in Table I. Resin infusion was performed at ambient temperature perpendicular to the yarn axis to generate uniform resin flow. A schematic diagram of the infusion mould is shown in Fig. 2. Before infusion, mould release was applied (4−5 times) to the mould, square frame and the picture frame and allowed to dry.



(a)

(b)

Fig. 2. (a) Infusion mould (b) infusion set up.

After infusion, the tool was kept closed overnight for curing of the resin. The composite plaques were then post-cured for six hours at 60 ºC inside an oven, placed between two pieces of glass fibre composites with weight added to avoid warping.

IV. TESTING

A. Single Yarn Tensile Test

Unsized hairy and hairless yarns were tested for tensile properties. The test was performed with reference to BS ISO 3341:2000 using a Hounsfield Series-S machine with a cross head speed of 1 mm min^{-1}, gauge length 250 mm and a 500 N load cell (Software-QMAT). Double sided adhesive tape was wrapped around the circular jaw and yarn was wrapped on this for gripping. The distance between centres of the jaws was considered as the gauge length. 10 tests were performed for each type of yarn to find the mean value of tensile

properties. The highest value of gradient of force-displacement curve of yarn was calculated every 0.5 mm extension [13] to find the tensile modulus. Mean diameter of yarns was determined from ten readings of images at or above 1 m length intervals taken by a Zeiss optical microscope. Yarn cross-section was enumerated considering a circular cross-section of yarn and the packing fraction of yarn (ratio between apparent cross-section and actual cross-section of yarn) is considered to be 0.6 (as determined by Shah *et al.* [13] for the same yarn). The failure load of the yarn obtained from the tensile test was converted to tenacity (cN/Tex) [14]. Failure load of yarn was obtained in Newtons (N) and transformed to cN/Tex according to the Eq. (1):

$$\text{cN/Tex}=(\text{N}\times 100)/\text{ Yarn count in Tex} \quad (1)$$

B. X-Ray Photoelectron Spectroscopy (XPS) Analysis

XPS analysis of hairy and hairless yarns was performed to observe any surface chemical changes and to examine the effects of burning the fibres. A VG Scientific ESCALab Mark II x-ray photoelectron spectrometer was used in order to characterise the fibre surfaces, utilising non-monochromatic Al Kα X-rays at an anode potential of 15 kV and filament emission current of 20 mA. Survey (wide scan) spectra were collected at an electron pass energy of 50 eV within the 0−1200 binding energy range in order to ensure all peaks in the samples are present in the spectra. Subsequent data processing and peak labelling of spectra were performed using CasaXPS software.

C. Differential Scanning Calorimetry (DSC) Analysis

DSC thermograms were taken using TA instruments, USA, model DSC Q10 in a nitrogen atmosphere (gas flow rate 50ml min^{-1}) for hairy and hairless yarns to understand any thermal degradation of fibres due to burning hairs. A constant heating rate of 10 ^oC min^{-1} was used from 0 ^oC to 400 ^oC for fibres and post-cured resin and 0 ^oC to 350 ^oC for liquid resin and composites. A sample size of approximately 10mg was used in a Tzero aluminium pan crimped with a pinhole. Data acquisition and processing was performed using TA Universal Analysis 2000 software. A blank pan measurement was conducted for background study. Liquid resin, post cured composites made with unsized hairy and hairless yarns were also analysed to obtain DSC thermograms to understand their curing behaviour.

D. Fourier Transform Infrared (FTIR) Spectroscopy Analysis

Identification of functional groups of the hairy and hairless yarns was performed using FTIR (Tensor-27, Bruker). All spectra were analysed with Opus™ software version 5.5. Both yarn types are scanned in transmittance mode in the region of 4000 cm^{-1} and 550 cm^{-1} (wave numbers) using a standard pike Attenuated Total Reflectance (ATR) cell (Pike Technology, UK). After every test the spectrometer is cleaned using acetone.

E. Composite Tensile Test

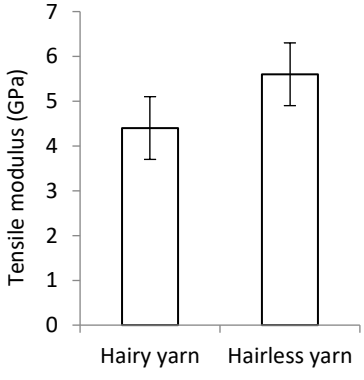
Composite plaques were stored at ambient conditions for at least 48 hours after post-curing prior to conducting any test. Before performing tensile tests, the fibre volume fraction of the composites was determined. As mentioned in 'Manufacturing of composites' section the mass of the fibres was measured before infusion and the volume of the fibres is calculated considering the density of jute fibre 1.45 g/cm^3 [15]. The volume of the composite plaque was determined by measuring length, width and thickness. At least three readings were taken for each dimension and the mean values were considered for calculating the volume of the composite plaque. Fibre volume fraction of composites was obtained by dividing the volume of fibres by the volume of the composite plaque. As the fibre volume fraction of composites was measured for the whole plaque thus standard deviation is not available.

Composite tensile tests were conducted with reference to BS EN ISO 527-4:1997 using an Instron 5969 fitted with a 50 kN load cell (software Bluehill®) and a mechanical extensometer. The cross-head speed was 1 mm min^{-1}. Plaques were tested along the longitudinal and transverse direction of yarns. Five tests were performed for each plaque to find the mean values of tensile properties. Tests were performed at ambient condition (15–25 ^oC and 60–90% RH).

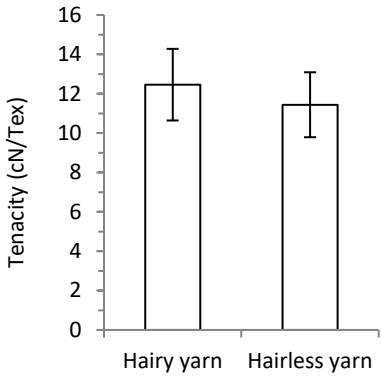
V. Results And Discussion

A. Single Yarn Test Results

The removal of yarn hairs by burning brings the possibility of deteriorating the tensile properties of hairless yarn due to possible damage of thermally unstable constituents of jute fibre at higher temperature [16–18]. Thus studying tensile properties of hairy and hairless yarn is of interest, since any damage of yarn would affect the mechanical properties of composites. However tensile modulus of hairless yarn was found to be 24% higher than that of hairy yarn (Fig. 3 (a)) and this difference is statistically significant (from student's t-test $P<0.05$). Hairs practically have no effect on tensile properties of yarn. Hence the increase in tensile modulus of hairless yarn established that burning hairs did not deteriorate this property and increase in tensile modulus is due to the wide range of variation of property of jute fibre. Very similar standard deviations are obtained for tensile moduli of yarns. A minor difference is found between tenacity of hairy and hairless yarn (Fig. 3 (b)) revealing that burning of hairs does not deteriorate the tensile strength.



(a)



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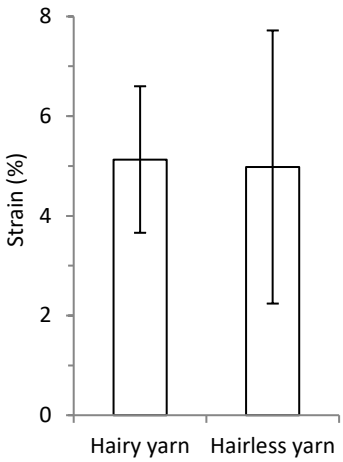

(c)

Fig. 3. Tensile modulus (a), tenacity (b) and strain at failure of yarn (c) (error bars indicate standard deviation).

Standard deviations of tenacity of both types of yarn are also similar. Strain at failure of hairy yarn and hairless yarn is found to be very similar, however the standard deviation of strain at failure (Fig. 3 (c)) of hairless yarn is higher than that of hairy yarn. Wide range of variation of property is the inherent character of natural fibres, which is very prominent here.

B. XPS Analysis for Surface Chemicals of Hairy and Hairless Yarns

A study of x-ray photoelectron spectroscopy presents some variations of surface composition of hairy and hairless yarns. 5.4% higher carbon (C) content and 4.4% lower oxygen (O) content (Table II) are observed on hairless yarn surface with respect to those of hairy yarn surface. Exposing yarn under open flame increases unburnt carbon deposition on the surface. Most likely the amount of other elements are the same before and after burning. However, deposition of unburnt carbon on the yarn surface increases the carbon content hence reduces the proportions of other elements.

TABLE II: SURFACE CHEMICALS OF HAIRY AND HAIRLESS YARNS

Type of yarn	Carbon%	Oxygen%	Nitrogen%	Silicon%
Hairy yarn	68.2	27	2.5	2.3
Hairless yarn	78.6	22.6	1.6	2.2

C. Thermal Analysis

DSC analysis was performed on hairy yarn, hairless yarn, composites made with hairy yarns, composites made with hairless yarns, post-cured and liquid polyester resin to understand their thermal behaviour. DSC thermograms of hairy and hairless yarns were found to be very similar (Fig. 4). An extended endothermic peak is observed in the temperature range 75–160 °C for both the types of yarn due to vaporisation of moisture absorbed by fibres [19]. Between 160–200 °C a small exothermic peak is observed and is due to decomposition of lignin [19]. No peak is found between 200–260 °C which reflects the thermal stability of fibre in this region. A small exothermic peak around 260–280 °C indicates the decomposition of hemicellulose [20] Major changes start around 300 °C as cellulose decomposes at this temperature [21].

The DSC thermogram of post-cured resin does not show any major change up to 325 °C. Around this temperature it starts to decompose and at around 400 °C it decomposes fully. A quasi-linear relationship up to the start of decomposition suggests the resin is fully cured and it can be exposed safely up to 325 °C. Characteristics of DSC thermograms of composites made with hairy and hairless yarns are closer to that of jute fibres than that of post-cured resin. Endothermic peaks due to evaporation of moisture of jute fibre in DSC thermograms of composites are obvious and composites start to decompose at a similar temperature to that for jute fibres which is lower than for post-cured resin (Fig. 4). Hence this reflects that thermal change of composites is influenced mostly by jute. The DSC thermogram of liquid polyester resin shows an extended exothermal peak in the temperature range 50 °C to 135 °C due to the exothermic reaction of resin as it forms a cross-linked structure.

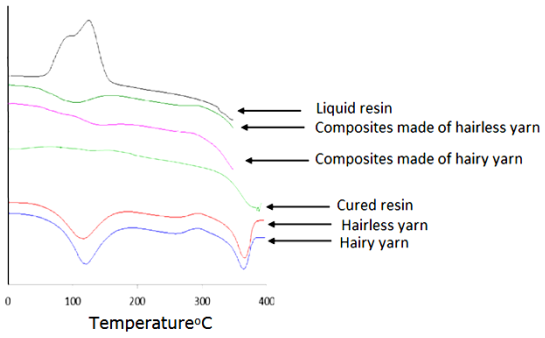

Fig. 4. DSC thermograms of yarns, composites and polyester resin.

D. Fourier Transform Infrared (FTIR) Analysis

FTIR spectra of hairy and hairless yarns are shown in Fig. 5 from wave number 4000 cm^{-1} to 500 cm^{-1}. Both spectra are very similar regarding the peak position, revealing that no major change of chemical composition of fibres has occurred due to burning. The absorption band in the region 3346 cm^{-1} represents O-H stretching vibration of cellulose [22, 23]. The peak near 2900 cm^{-1} is due to C-H stretching vibration of methyl and methylene groups presents in cellulose and hemicelluloses [24]. A sharp peak at 1740 cm^{-1} is due to the C-O stretching of the carboxyl and acetyle groups in hemicelluloses [22]. Vibration at 1647 cm^{-1} is assigned to aromatic rings [25] of lignin [26].

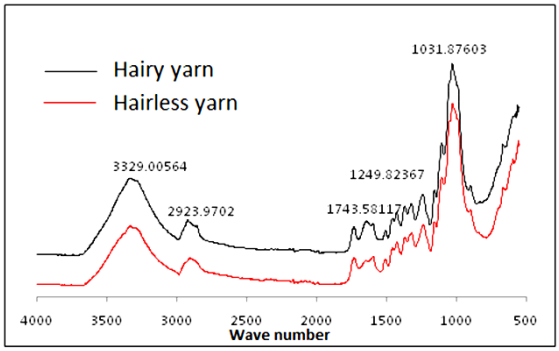

Fig. 5. FTIR spectra of hairy and hairless yarn.

The peaks at 1596 cm^{-1}, 1510 cm^{-1} and 1323 cm^{-1} are attributed to lignin or phenolic compounds [26]. The absorbency band at 1463 cm^{-1} represents -CH_3 deformation (asymmetric) in lignin [22]. The absorbance at 1373 cm^{-1} is a characteristic absorbance associated with C-H deformation (symmetric), which may be due to lignin, cellulose and xylan [22]. The absorbency band at 1247 cm^{-1} is assigned to C-O stretching of acetyle in xylan and the band at 1031 cm^{-1} is ascribed to aromatic C-H and C-O deformation of primary alcohol in lignin [22].

E. Composite Test Results

1) Longitudinal direction of yarn: Composites made with unsized hairy yarns show 5.5% higher tensile modulus with respect to composites made with unsized hairless yarns (Fig. 6) and this difference is statistically significant ($P < 0.05$). Composites made with unsized hairy yarns show 7.5% lower strain at failure with respect to composites made with unsized hairless yarns (Fig. 8) and this difference is statistically significant ($P < 0.05$). Even taking into consideration the slight different fibre volume fraction (35–38%) this significant difference in properties is probably due to yarn hairiness. The projected hairs from the yarn surface embedded in resin possibly contribute better initial stress transfer during tensile loading that helps to increase the tensile modulus. Strain at failure of composites (Fig. 9) is much lower than that of polyester resin (Table I) and this property of composites in the longitudinal direction of yarn is governed by the strain at failure of fibre. Hence it is obvious that natural variability of fibre is only responsible for increasing strain at failure of unsized hairless composites. A similar trend is observed for tensile modulus and strain at failure of composites manufactured with HEC sized hairy and HEC sized hairless yarns, however the differences are less pronounced. Hairs laid on the yarn surface due to sizing possibly do not contribute to the tensile properties of composites as much as for composites made with unsized yarn. The tensile strengths of composites manufactured with hairy and hairless yarn (Fig. 7) do not show statistically significant differences for any of the cases (i.e., sized and unsized). Stress-strain curves of UD jute composites in the longitudinal direction of yarn are presented in Fig. 9. An initial linear portion, an extended curved region and again a linear portion with lower slope are observed for each plaque. Characteristics of the curves obtained from different plaques of composites are similar. Similar behaviour of stress-strain curves of UD composites were found by Dwaikat *et al.* [27] and Rozite *et al.* [28]. The initial linear portion of the stress-strain curve during tensile loading is clearly visible, and when micro cracking of the matrix starts, the stiffness of the composites falls. This micro cracking occurs over an extended period and during micro cracking of the matrix there may be an extension of composites due to minor straightening of helically configured fibres, resulting in an effective reduction in stiffness. Propagation of matrix cracking continues with increasing load and the composite fails.

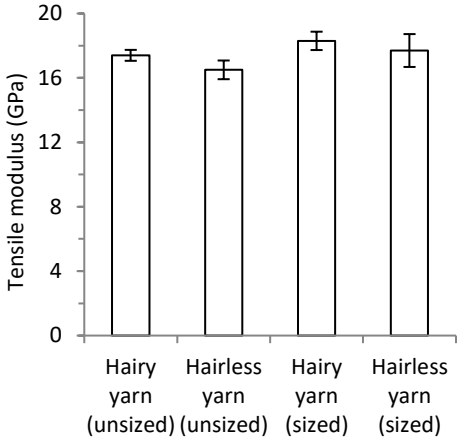

Fig. 6. Tensile modulus of composites.

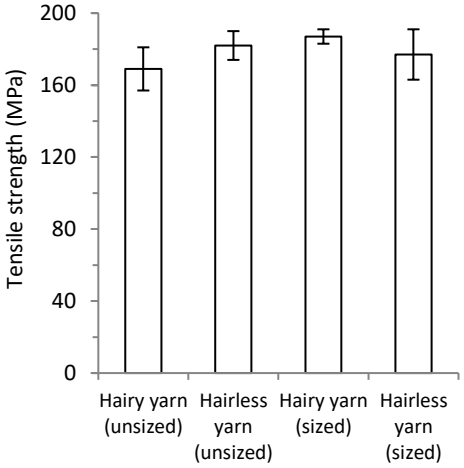

Fig 7. Tensile strength of composites.

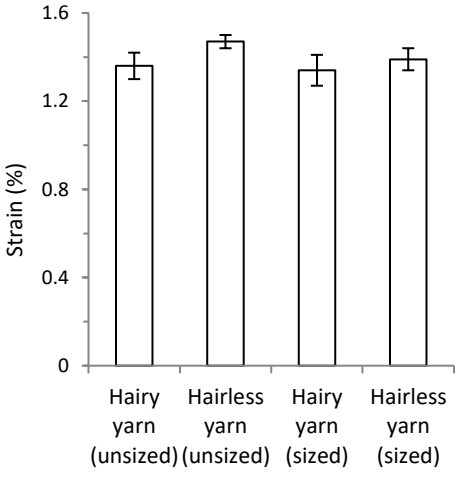

Fig. 8. Strain at failure of composites.

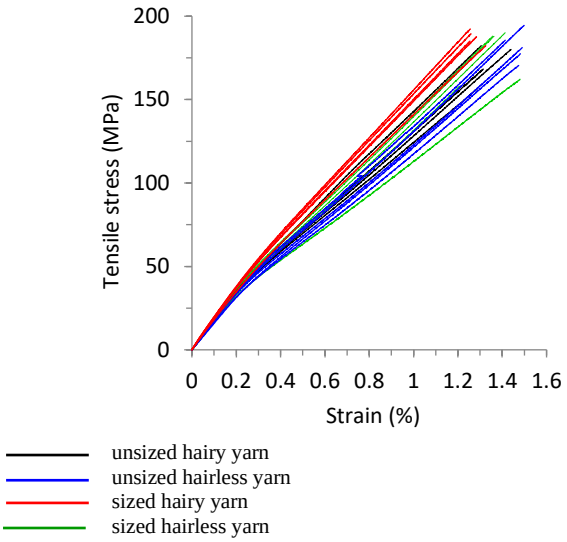

Fig. 9. Stress-strain curves of composites.

2) Transverse direction of yarn: Composites manufactured with unsized hairy and hairless yarn tested here possess similar fibre volume fraction (34–36%). Tensile modulus (Fig. 10) and tensile strength (Fig. 11) of these composite plaques do not show any statistically significant difference ($P < 0.05$). However, composites made with unsized hairy yarns shows 86% (Fig. 12) higher strain at failure with respect to composites manufactured with unsized hairless yarns in the transverse direction and this difference is statistically significant ($P < 0.05$). From Fig. 13, it is clear that after a certain level of strain (around 0.3%, which is very close to strain at failure of composites manufactured with unsized hairless yarn) there is almost no increase in stress. The increase in strain after this level is possibly due to bonding between yarn hairs and resin. Very similar tensile modulus and similar strain at failure are observed for composites manufactured with sized hairy and hairless yarn.

Composites manufactured with sized hairless yarn show 26% increase in tensile strength with respect to composites manufactured with sized hairy yarn (Fig. 11) which is statistically significant. As sizing is performed for both types of yarns, resulting in a smooth surface as if the yarn is hairless, no specific reason is identified as a cause of significant variation of tensile properties.

Highly anisotropic plant fibres [29] cannot improve the tensile properties of composites in the transverse direction and the tensile modulus of composites in the transverse direction is very similar to the tensile modulus of resin and the tensile strength of composites is much lower than that of resin (compared to Table I).

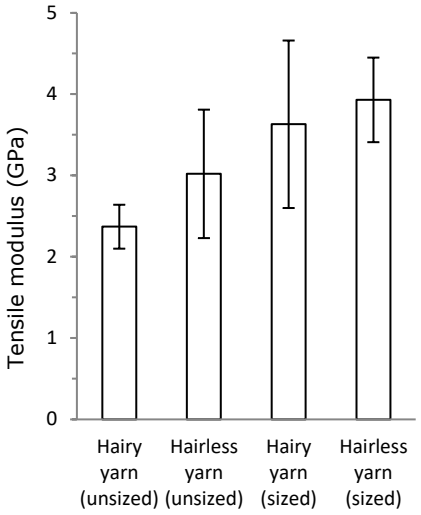

Fig. 10. Tensile modulus of composites.

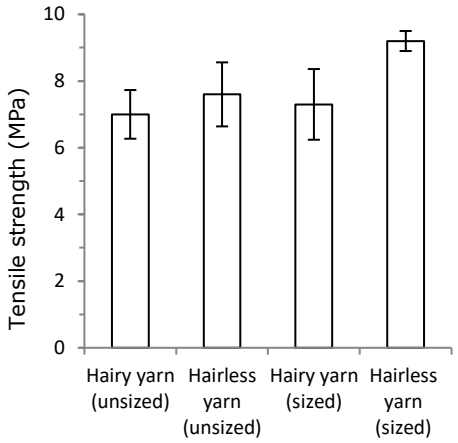

Fig. 11. Tensile strength of composites.

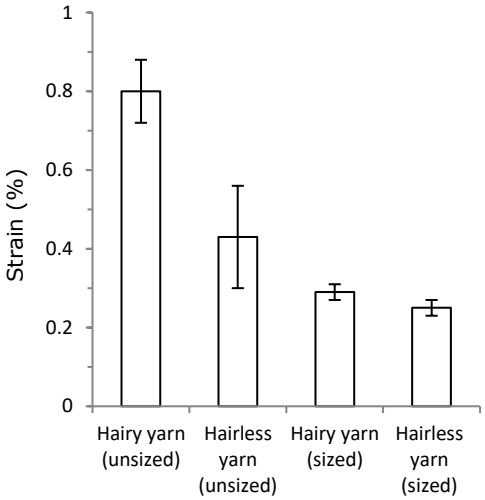

Fig. 12. Strain at failure of composites.

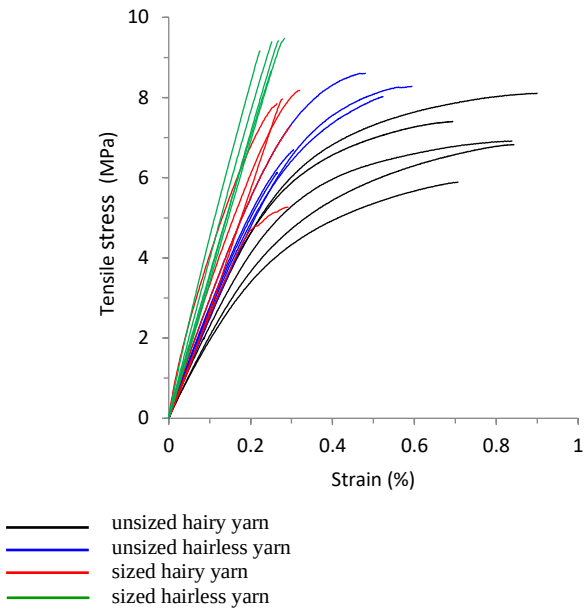

Fig. 13. Stress-strain curves of composites.

Stress-strain curves of composites manufactured with unsized hairy yarns (Fig. 13) show an initial linear portion, an extended curved region and again a linear portion which is similar to the curves obtained in the longitudinal direction. Thus a similar explanation is also valid here, however the curved region and second linear portion in the transverse direction are due to the bonds between hairs and resin. As bonds between hairs and resin are unable to carry significant stresses, at the end of the curved region (around 0.3% strain) a significant increase in strain is observed for a small increase in stress. Stress-strain curves of composites manufactured with unsized hairless yarns (Fig. 13) show an initial linear portion and an extended curved region. As the manual burning process cannot remove all hairs thus bonds between remaining hairs and resin may be responsible for the curved region for composites manufactured with unsized hairless yarn. However, stress-strain curves of composites manufactured with sized yarns (Fig. 13) show only linear behaviour. The surface of sized yarns (hairy and hairless) becomes smooth (see Fig. 1) thus linear stress-strain curves occur with low strain at failure. Large standard deviations of the tensile properties of composites in the transverse direction are observed, which is very common for plant fibre composites due to natural variations in properties.

VI. Conclusions

From this work the following findings can be summarised.

Burning of hairs by candle flame does not affect the failure load of yarn. DSC and FTIR analysis of hairy and hairless yarns show no major change of properties due to burning of hairs. However, XPS studies present differences of surface chemicals between hairy and hairless yarn, with hairless yarn show higher carbon, less oxygen and less nitrogen content than hairy yarn.

Yarn hairiness affects the tensile modulus and strain at failure of UD composites in the longitudinal direction and strain at failure in the transverse direction of yarns. An increase in tensile modulus as well as a decrease in strain at failure of composites manufactured with unsized hairy yarn is observed with respect to composites manufactured with unsized hairless yarn in the longitudinal direction. An increase in tensile modulus of composites manufactured with hairy yarn could be of interest for composite manufacturers and may reduce the work load of the spinner, as spinners usually attempt to reduce the hairiness of yarn which is a prime requirement for most applications of textiles.

Removing hairs is the principle challenge of this research work. Burning hairs using flame can easily damage or burn yarn. Removing hairs by enzyme treatment also can deteriorate yarn properties. Hence this operation must be performed carefully.

This research work was performed on tossa jute yarn. Hence there are some opportunities to investigate the effect of hairiness on the properties of composites by other yarn. Also, the variation of hairiness such as length or density of hairiness effect can be studied.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

R. K. Nag conducted the research, Visualized and wrote the research; A. C. Long and M. J. Clifford made supervision and validation for the research. All authors had approved the final version.

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