Mechanical Properties of Flax-Polypropylene Composites from Dry Flexible Towpregs: Influence of Radial Position of Flax Fibers in the Towpreg

Vijay Goud A, Ashraf Nawaz Khan A, Alagirusamy Ramasamy A, Apurba Das A and Dinesh Kalyanasundaram A, B, C

A Department of Textile and Fiber Engineering, Indian Institute of Technology Delhi, New Delhi, India; B Centre for Biomedical Engineering, Indian Institute of Technology Delhi, New Delhi, India; C Department of Biomedical Engineering, All India Institute of Medical Sciences, New Delhi, India

ABSTRACT

The radial position of the flax fibers as reinforcement and polypropylene (pp) fibers as matrix was altered using friction spinning in three distinctive sequences from core to sheath, namely, (a) pp-flax-flax-pp (PFP), (b) flax-pp-flax-pp (FPFP), and (c) flax-flax-pp-pp (FPFP). Interestingly, at the towpregs stage, PFP demonstrated higher tensile characteristics than FPFP and FPFP. The towpregs were consolidated to yield three unidirectional composites (UDCs), namely, UDC-PFP, UDC-FPFP, and UDC-FPFP, using compression molding. The tensile strength of the composites (σ_{UDC-PFP} > σ_{UDC-FPFP} > σ_{UDC-FPFP}) was contrary to the breaking load (f) of the corresponding towpregs (f_{PFP} < f_{FPFP} < f_{FPFP}) which necessitated the current investigation. Remarkably, the UDC with the lowest tensile as well as interlaminar shear strength i.e. UDC-FPFP, yielded the maximum energy absorption in Charpy and Notch impact tests. In the towpreg, the flax fibers when placed at the core position, slid over each other resulting in poor strength in FPFP while post-curing the pp matrix impregnated the core flax fibers in UDC-FPFP, resulting in the highest strength amongst the three UDCs in tensile and flexural modes. Micro-computed tomography (µCT) was carried out to confirm the same. Thus, the user can select the requisite fiber-matrix radial positions within towpreg to suit the ultimate applications.

KEYWORDS

Flexible towpreg; natural flax fibers; radial position; damage mechanics; mechanical testing; Micro-CT

ABSTRACT

使用摩擦纺纱以三种不同的顺序从芯到鞘变化作为增强体的亚麻纤维和作为基体的聚丙烯（pp）纤维的径向位置，即: (a) 聚丙烯-亚麻 pp (PFP)，(b) 亚麻-聚丙烯-亚麻聚丙烯 (FPFP) 和 (c) 亚麻-亚麻 pp (FPFP)。有趣的是，在 towpregs 阶段，PFP 表现出比 FPFP 和 FPFP 更高的拉伸特性。使用压缩模塑，将丝束预浸料固结以产生三种单向复合材料 (UDC)，即 UDC-PFP、UDC-FPFP 和 UDC-FPFP。复合材料的拉伸强度 (σ_{UDC-FPFP} > σ_{UDC-PFP} > σ_{UDC-FPFP})。值得注意的是，具有最低拉伸强度和层间剪切强度的 UDC，即 UDC-PFP，在夏比和缺口冲击试验中产生最大能量吸收。在 towpreg 中，当放置在芯部位置时，亚麻纤维彼此滑动，导致 FPFP 中的强度差，而在后固化时，pp 基体将芯部亚麻纤维浸渍在 UDC-FPFP 中，导致在拉伸和弯曲模式下三种 UDC 中的强度最高。进行了显微计算机断层扫描（µCT）以证实这一点。因此，用户可以在 towpreg 内选择必要的纤维基体径向位置，以适应最终应用。

CONTACT Ashraf Nawaz Khan khanashraf90@gmail.com  Yarn Manufacturing Lab, Department of Textile and Fiber Engineering, Indian Institute of Technology Delhi, New Delhi, 110016, India

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**Introduction**

Natural fibers as reinforcement in composites are finding potential applications in automobile, packaging, sports, and civil engineering sectors (Mahesh et al. 2022). Most commonly used natural fibers for composite reinforcement are flax, jute, hemp, sisal, banana, Kenaf, bamboo, silk, palmyra etc. (Genc and Ozdemir 2020). Presently, flax is gaining widespread use (Çelik and Alp 2022). It is a decomposable and environmental-friendly (i.e., on ignition, it does not release toxic gases) fiber (Selmi et al. 2022). Moreover, the apprehensions with the safety and health during handling and processing are negligible (Malik et al. 2021).

Flax fibers as reinforcement are compatible with polymeric matrices when compared to metal and ceramic matrices. Among the polymeric matrices, thermoplastic matrices are easier to process, simpler to handle, possess unlimited shelf life at room temperature, have higher toughness and most prominently are recyclable and do not liberate volatile organic compounds in contrast to thermoset matrices (Goud et al. 2019b; Khan et al. 2022a). The foremost difficulty with utilization of thermoplastic matrix in continuous fiber composite applications is its higher melt viscosity (Agaliotis, Morales-Arias, and Bernal 2021). As a result of excessive viscosity of thermoplastic matrices, it is almost impossible to achieve thorough infusion of matrix into the continuous fiber reinforcement (Goud et al. 2018; Khan et al. 2022b). The prospective solution to this problem is to mix the reinforcement with matrix preceding the formation of final shape to produce a towpreg (Jogur et al. 2019). The processes such as hot melt impregnation and solvent impregnation merge reinforcement and matrix, in molten stage and liquid stage, respectively. This leads to the formation of stiff towpregs which are not suitable for textile preforming operations (Goud et al. 2019a). Thus, mixing of reinforcement and matrix in dry form gained popularity. The processes which combine reinforcement and matrix in dry form such as friction spinning, micro-braiding, parallel winding, wrap spinning, commingling and powder coating received remarkable consideration (Alagirusamy et al. 2010; Khan, Mahajan, and Alagirusamy 2022c).

Amongst these processes, friction spinning process has gained wide acceptance owing to its higher production speed and production of core-sheath yarn with versatility to customize the fiber-to-matrix ratio (Goud et al. 2020).

Friction spinning principle provides various possibilities for hybridization (Bhowmick, Rakshit, and Chattopadhyay 2020). In friction spinning, fibers are assembled between the friction drums layer by layer. Fibers from the sliver fed at the farthest position from yarn collection point goes into the core of the yarn, and the fibers from subsequent slivers keep wrapping on the previously formed layers as the yarn is moving toward the collection point. There is a pre-determined gap set between the two perforated friction drums. The first fibers arriving from the farthest sliver gets collected between the rotating drums due to suction and start rolling due to the rotation of the drums, but no significant twisting torque is developed in these fibers till the collected fiber mass gets compressed, and the compressed mass attains a diameter equal to the width of the gap between the drums. This fiber mass with least twist forms the core of the yarn. Fibers arriving later from other slivers get wrapped on this core layer by layer. As the yarn diameter increases, the twisting torque acting on the fibers due to the friction force provided by the rotating friction drums and the twist keep on increasing till the yarn is formed completely (Merati et al. 1998). Since the ratio of yarn take-up speed and rotational rate of friction drums is constant, the fibers located at the lower yarn radial position will subtend lower angle with the axis of the yarn as compared to those located at larger radial positions. Hence, the fibers in core are more aligned with the yarn axis with lesser twist.

The mechanics of strength development in hybrid yarn and the composites are quite different. Hence, it is hypothesized that the relative radial positioning of the reinforcing flax fibers and the matrix forming pp fibers are expected to contribute differently in the yarn and the composites. This important aspect has not been investigated so far in the literature. In the present investigation, the flax fiber as reinforcement and pp as matrix are positioned in three different configurations within the cross-section of the friction spun towpreg. The towpreg produced with altered radial positions within the cross-section of the friction spun towpreg are pp-flax-flax-pp (PFPF), flax-pp-flax-pp (FPFP), and
flax-flax-pp-pp (FFPP). These towpregs were used in the production of the unidirectional composites (UDC), namely, UDC-FFPP, UDC-FPFP, and UDC-PFFP from FFPP, FPFP, and PFFP friction spun towpregs, respectively. The produced UDCs are investigated for their mechanical characteristics.

Materials and methods

Materials and characterization

Friction spun towpreg produced for present research study comprises of flax fibers and pp fibers. Flax fibers in the form of sliver (4 Ktex) was acquired from M/s. Jayshree Textiles Limited, West Bengal, India, whereas pp sliver (4 Ktex) was obtained from M/s. Zenith fibers Limited, Gujarat, India. The properties of flax and pp fibers are reported in the supplementary section (Tables S1, S2, and S3). Differential scanning calorimetry (DSC) and Thermogravimetric analysis (TGA) for pp slivers were carried out to determine the melting temperature and degradation temperature, respectively. DSC analysis for pp fibers is shown in Figure S1(a). The instrument provided 170°C as the melting point where the endothermic peak occurs. An endothermic heat of fusion of 84.96 kJ/kg was observed during the analysis. The existence of slumps signifies the presence of other compounds in the pp sample and may correspond to the spin-finish coating during the manufacturing of pp fibers. The TGA plot for pp fibers is illustrated in Figure S1(b). TGA analysis indicates the beginning of degradation at 315°C. By 400°C, 20% weight loss was witnessed. The processing temperature for consolidation in compression molding was maintained at 210°C.

Methods

Production of friction spun towpregs

Two flax slivers and two pp slivers were simultaneously fed through the Draft Unit I of the friction spinning machine (DREF 3000, Malaysia). The schematic diagram of the friction spinning machine is shown in Figure 1a. The flax sliver and pp slivers were fed in three distinctive orders of arrangement. In the first order, two flax slivers were sandwiched in between two pp slivers (PFFP). The second order involved alternate arrangement of flax and pp slivers i.e., FPFP. The final order consisted of two flax slivers followed by two pp slivers in FFPP arrangement. For the sake of clarity, the three different configurations are shown in Figure 1b–d with various slivers in the radial position.

For the production of the towpregs in the radial form, the first indicated material type i.e., “flax” indicated by “F” in FPFP occupies the extreme left position (farthest from the yarn take-up position) and takes up the core position in the yarn, whereas the last material type, say “pp” denoted by “P” in this example, holds the extreme right position in the feed zone thereby forming the sheath in the yarn (Figure 1). Similarly, the combinations of FFPP and PFFP were produced with different radial positions of reinforcement and matrix. The process parameters for production of friction towpregs are presented in the supplementary section. These three different configurations of friction spun towpregs were used for production of UDCs. Details of the production of the UDCs using three different configurations of friction spun towpreg are reported in Table 1.

Production of unidirectional composites

The schematic diagram of the metallic frame and the molds used in the production of unidirectional composites is shown in Figure 2. The friction spun towpregs as mentioned in the earlier section were looped around a metallic casing in a parallel mode. The length and width of winding around the metallic framework were 350 mm and 25 mm, respectively. The number of turns in four layers around the metallic frame to a width of 25 mm was 72. The wrapped friction spun towpregs were placed in the mold cavity with 3 mm spacing along the thickness. Similar wrapping and placement in the mold cavity were ensured for flexural test specimens as well. On the other hand, for interlaminar shear
Figure 1. (a) Schematic diagram of towpreg manufacturing with varying positions of flax and pp through friction spinning process and schematic representation of the towpreg cross-section and longitudinal view with different radial position for flax reinforcement and pp matrix: (b) PFFP, (c) FFPF, (d) FFPP.

strength as well as Charpy and notch impact specimen the friction spun towpreg was wound in eight layers to a width of 12 mm to achieve a number of turns of 80, around a metallic frame of 350 mm length. The wrapped friction spun towpreg was placed in a mold cavity of 250 mm in length, 13 mm in width, and 6 mm in depth.

Compression molding machine was used for consolidation of friction spun towpreg positioned in the mold cavity. Prior to the beginning of the consolidation cycle, the sample was exposed to three breathing cycles of 15 seconds each under the breathing pressure of 40 bar. The breathing cycle

| Matrix  | Reinforcement | Sequential arrangement of entry of slivers from core (extreme left) to sheath (extreme right) into Drafting system of friction spinning | Friction spun towpreg of 400 tex | Unidirectional composites (UDC) on consolidation of parallel wound friction towpreg placed in mold cavity |
|---------|---------------|------------------------------------------------------------------------------------------------------------------|---------------------------------|---------------------------------------------------------------------------------------------------|
| pp sliver | Flax sliver   | ppi/ flax/ flax/pp (PFFP)                                                                                         | PFFP                            | UDC-PFFP                                                                                          |
| pp sliver | Flax sliver   | flax/ppi flax/pp (FFPP)                                                                                           | FPFP                            | UDC-FPFP                                                                                          |
| pp sliver | Flax sliver   | flax/flax/pp/pp (FFFP)                                                                                           | FFPP                            | UDC-FFP                                                                                           |
ensured the elimination of air pockets within and between the towpregs. The parameters used for consolidation of the unidirectional composites were 40 bar pressure, 210°C temperature, and time duration of 900 seconds. At the end of the molding cycle, the specimen was cooled under pressure of 40 bar till the temperature of the platen dropped below 80°C. Once cooled, the samples were removed from the mold cavity. The anti-stick silicon spray (Afra heavy duty silicone spray, Uttar Pradesh, India) applied into the cavity of the top and bottom mold prior to placement of wrapped towpreg ensured smooth removal without damaging the surface characteristics of the composites produced. The unidirectional composites were produced with a fiber volume fraction of 42% and thickness of 3 mm.

**Determination of properties of friction spun towpreg**

**Tensile strength and modulus**
The produced towpregs were tested for their tensile properties as per ASTM D2256 on Universal Testing machine (Instron, Model 5982, Massachusetts, USA).

**Determination of unidirectional composite (UDC) properties**

**Tensile strength and modulus**
ASTM D3039/D3039M-17 was employed for the determination of tensile properties of the unidirectional composites. Five specimens each with a dimension of 250 mm (length) × 25 mm (width) × 3 mm (thickness) were tested on Universal Testing machine (Instron, Model 5982, Massachusetts, USA). Advanced video extensometer (Model No: 2663-901, Instron, USA) was used for precise determination of the strain on the composite as shown in the supplementary section. The tensile specimens were sprayed with white acrylic paint and black dots were marked on the sample. The movement of black dots provided an exact measurement of the elongation of the sample eliminating the probability of error induced due to slippage of sample in the jaw.

**Flexural strength and modulus**
The flexural strength and modulus of the composite were tested and evaluated using ASTM D7264/D7264M-15. In order to minimize the shear component and ensure pure bending behavior, a span-to-thickness ratio of 32:1 was implemented on Universal Testing Machine (Instron, Model 5982, Massachusetts, USA).
**Interlaminar shear strength**

Short beam tests were conducted to determine interlaminar shear properties of the unidirectional composites. A span-to-thickness ratio of 4:1 was chosen for interlaminar shear tests as per ASTM D2344/D2344M-16. The thickness of the composites produced was 6 ± 0.2 mm. To ensure span-to-thickness ratio of 4:1, 24 mm support span was maintained between the two rollers on the bottom jaw.

**Notch impact energy absorption**

Izod notch impact test was performed as per ASTM D256. Izod impact tester (Model: IT 504 plastic impacts, Tinius, Olsen, USA) was employed for the experimentations. Five numbers of specimens were assessed for each of the three varieties of the composites. The composite samples were cut to 64 mm (length) × 13 mm (width). The pendulum with an energy of 15 J was found to be sufficient for the propagation of the notched crack.

**Charpy impact energy absorption**

Charpy impact tests were accomplished as per ASTM D6110-18. The machine used, the dimensions of the samples, and the test parameters were as aforementioned for Notch impact energy absorption test.

**Micro-computed tomography (µCT)**

X-ray micro-computed tomography (Model: µ-CT-50, Scanco Medical, Bassersdorf, Switzerland) was used to study the internal failure mechanism involved during the Interlaminar shear strength (ILSS) test. The samples were placed in a 19-mm diameter carousel holder for imaging. The dimension of samples was 13 mm (width) × 6 mm (thickness) × 14 mm (scanning length). There were approximately 1400 slices for the scanned specimens. The X-ray voltage of 70 kV was used with the current intensity of 133 µA to scan the specimens and the voxel size was 6 µm. The samples were rotated by 360° angle to capture 2D images. The region of interest was defined manually, and the same threshold values were kept for all the specimens. A 3D reconstruction of 2D X-ray images was obtained with the help of the Scanco Medical reconstruction software.

**Results and discussion**

**Tensile properties of towpreg**

The properties of flax and pp fibers are provided in the supplementary section. The tensile properties of the friction spun towpregs with discrete positioning of the flax and pp within the cross-section (PFFP, FPFP, and FFPP) are reported in Table 2. A typical load versus extension behavior of the produced friction spun towpregs is shown in Figure 3a. Amongst the produced conformations of friction spun towpregs, PFFP gives the maximum load carrying capacity, whereas FFPP demonstrates

| Sample          | Tensile properties of friction spun towpreg |
|-----------------|--------------------------------------------|
| Friction spun towpreg | Average Breaking Load (N) (standard deviation) | Average Breaking Extension (mm) (standard deviation) |
| PFFP            | 22.5 (±3.05)                               | 65.4 (±12.81)   |
| FPFP            | 19.5 (±2.19)                               | 42.5 (±5.84)    |
| FFPP            | 10.7 (±2.52)                               | 30.2 (±5.38)    |

**Table 2.** Tensile test results of PFFP, FPFP, and FFPP friction spun towpregs (n = 15).
Figure 3. (a) Load-extension plot for PFFP, FPFP, and FFPP friction spun towpregs (b) Tensile test results – Stress-Strain plot for UDC-PFFP, UDC-FPFP, and UDC-FFPP.

The least load bearing ability. The tensile breaking load of the hybrid yarn of FFPP was 45% and 52% lower than that of FPFP and PFFP, respectively. FPFP yielded the least extension while PFFP exhibited significantly higher extension. The elongation or extension of PFFP was 54% and 117% higher than FPFP and FFPP, respectively.

These observations clearly indicate that the towpregs where the relatively stronger flax fibers are positioned in the core of the towpreg show lower load bearing ability than that (PFFP) in which the flax fibers are located away from the core. The reason for this behavior is as follows: In friction spun yarns, the fibers placed in the core aligned more toward the axis with very little twist. Due to this, there is very less lateral pressure on the fibers. When the tensile load is applied on this strand, the fibers can easily slide past each other and hence is of lower tensile strength. Thus, FFPP structure of hybrid yarn exhibited the least tensile strength followed by PFFP.

The inherent lower extension of the flax fibers along with the lowest inclination toward the towpreg axis is the reason for the lowest extension of the FFPP towpreg. However, for PFFP towpreg, the flax fibers occupy the relatively outer radial position in comparison with FFPP, higher twist and better integrity is obtained amongst the flax fibers. On the application of a tensile load, higher frictional resistance between the flax fibers occurs due to the twist in flax fibers. Due to the higher resistance to the tensile load, higher tensile strength was observed in PFFP. Likewise, PFFP towpreg shows highest extension as a result of higher extensibility of pp fibers positioned in the core. On similar lines, the intermediate properties exhibited by FPFP towpreg can be explained.

**Tensile properties of UDC-PFFP, UDC-FPFP, and UDC-FFPP**

A characteristic stress-strain diagram of the three composites is represented in the Figure 3b. The average values of tensile strength and modulus of elasticity of the manufactured UDC’s are given in Table 3. The maximum internal resistance to the employed load was demonstrated by UDC-FFPP as can be established from the Figure 3b. The ultimate stress borne by UDC-FFPP was 16% and 49% and greater than UDC-FPFP and UDC-PFFP, respectively.

It is interesting to note that the behavior of the UDCs is contrary to that of the corresponding towpregs. In the case of UDC-FFPP, the pp matrix on the outer layers undergoes melting during consolidation and impregnate into the yarn as well as fuse with the outer layers of the neighboring yarn (i.e. pp layer). With all the fibers aligned toward the axis of the towpreg/composite along with the
tight wrapping by the shrinking pp matrix, the flax fibers tend to endure higher proportion of the applied load. Relatively stronger flax fibers at the core are aligned in the axial/longitudinal direction of the composite in which the load is applied, thereby yielding the highest strength. In UDC-FPFP, the third layer of flax fibers from the core is twisted around the two inner layers of flax and pp.

As the flax fibers are twisted, the tensile strength of the towpreg reduces for two reasons. Firstly, on twisting, the fibers get oriented away from the load bearing axial direction, thereby reducing the tensile strength contribution along the axial direction by a factor of \( \cos^2\theta \) where \( \theta \) is the angle of inclination of the fiber with respect to the axial direction of the towpreg. Secondly, twist makes the flax fiber bundle more compact leading to poor penetration of the molten PP matrix into the flax fiber bundle during consolidation resulting in poor fiber wet out by the matrix material. It is also feasible that the inner most layer of pp (core layer) may not have undergone complete melting and impregnation as compared to the outermost layers. A schematic of the hypothesis is given in Figure 4.

The modulus of UDC-FFPP is 10% and 61% higher than UDC-FPFP and UDC-PFFP, respectively. The higher modulus of UDC-FFPP can be again attributed to the inherently higher modulus of parallel core of flax fibers impregnated by pp matrix. As, the flax fibers acquire the outer radial position, due to receipt of twist, the modulus tends to decrease. For, UDC-PFFP, the least modulus is expected as a result of lower modulus of pp.

**Figure 4.** Schematic of the arrangement of flax and pp in (a1, b1 and c1) towpreg and in (a2, b2 and c2) UDC-composites.
**Micro-computed tomography (µCT) analysis of cross-sections**

The scanned and reconstructed images of the µCT of the cross-sectional views of the three configurations are shown in Figure 5. UDC-PFFP configuration is shown in Figure 5a with pp material at the core surrounded by flax fibers indicated in red color. The two layers of flax fibers surrounding the core are seen as a ring while the outermost polymeric material has merged with the matrix of the neighboring towpregs. The UDC-FPFP configuration on the other hand has alternate fiber and polymer layers as seen in Figure 5b. The alternate arrangement of the two distinct materials into a well-dispersed composite is observed in this configuration. In the case of UDC-FFPP configuration (Figure 5c), the two consecutive flax fibers at the core are indicated by the red colored islands while the polymer matrix at the radially outward position has merged with the matrix of the neighboring towpregs to provide a distinct flax islands surrounded by the pp matrix. A comparison of the schematic proposed in Figure 4 and the micro-CT images in Figure 5a–c is concordant with each other. These images confirm the expected radial fiber distribution as planned during the sample production in friction spinning machine with the corresponding positioning of the slivers of flax and pp fibers.

Under flexural load, the typical plots of deflection as a function of the transverse load are shown in Figure 6a for the three UDCs. The mean values of the flexural strength and flexural modulus of the
produced UDCs are specified in Table 3. The highest resistance to deflection is displayed by UDC-FPFP which is 31% higher than UDC-PFP. Although UDC-FFPP displayed better flexural strength and flexural modulus numerically in comparison with UDC-FPFP, the result is not significant. Also, the flexural modulus of UDC-FFPP is 86% higher than that of UDC-PFP. Similarly, the flexural modulus of UDC-FPFP is 20% higher than that of UDC-PFP. As flexural testing generates tensile loading on one of the surfaces and compressive loading on the counter surface, the results are in agreement with the tensile experiments.

For the short beam tests, typical load-deflection plots for the fabricated UDCs are represented in the Figure 6b. The mean values of the short beam strength of the produced UDCs are specified in Table 4. The interlaminar shear strength exhibited by UDC-FFPP is 10% greater than UDC-PFP. Also, the short beam strength of UDC-FPFP is 4% higher than UDC-PFP. UDC-FPFP presented improved interlaminar shear strength numerically in comparison with UDC-FPFP, though the values are not significantly different. In case of UDC-PFP, the flax fibers are placed in the radial outer positions undergoing higher twist. The penetration of the matrix is highly affected due to the tightly twisted two layers of flax fibers, leading to resin rich and resin starved areas and weaker interfacial bonding between the reinforcement and the matrix. Thus, the samples failed at lower values of loads.

In the composite UDC-FPFP, merely one layer flax fibers acquire the core position where the twist is least within the cross-section of the towpreg, whereas remaining proportion of the flax fibers acquire considerably outer position and is thus highly twisted. As discussed earlier, the matrix infiltration within the highly twisted flax layers is poor. Insufficient matrix material present in this region leads to inadequate interfacial bonding resulting in failure via interlaminar failure. Non-axial alignment of loading bearing flax fibers in this region results in further reduction in the strength of the composite.

The fractured samples of short beam tests are shown in Figure 5. The 3D images [Figure 5 (a1 to c1)] as well as the longitudinally sectioned images [Figure 5 (a2 to c2)] of the fractured samples show fracture of fibers for UDC-FPFP configuration while UDC-PFP and UDC-FPFP indicate delamination/interlaminar failure. A uniform and larger cleavage can be observed in UDC-FPFP configuration. However, the tensile tests indicate higher strength (Figure 3b) for UDC-FPFP configuration. The strengths in these three configurations are mainly governed by the radial position of the flax fibers. When placed at the core, the strength of the pp matrix impregnated flax fibers is high and hence the composite shows the highest strength. As the flax fibers are displaced/offset from the core, the strength reduces in the same order i.e., \( \sigma_{\text{UDC-FPP}} > \sigma_{\text{UDC-FPFP}} > \sigma_{\text{UDC-PFP}} \). With flax fibers occupying outer radial position in both UDC-FPFP and UDC-PFP, the twist experienced by flax fibers resulted in diminished mechanical characteristics. It can also be noted that the composite UDC-FPFP shows better impregnation of polypropylene matrix with flax fibers. The fracture of the flax fibers and matrix occurred along a plane perpendicular to the flax fibers. No delamination of the layers is observed in UDC-FPFP unlike UDC-FPFP and UDC-PFP.

**Charpy and Izod Notch Impact properties of UDC-PFP, UDC-FPFP, and UDC-FPFP**

In Charpy Impact tests, UDC-PFP yields 64% and 28% higher impact energy absorption in comparison with UDC-FPFP and UDC-FPFP, respectively (Table 4). Similarly, in notch impact test, UDC-PFP (Table 4) absorbs 100% higher energy as against UDC-FPFP. Although UDC-PFP exhibits higher absolute value of impact energy absorption when compared to UDC-FPFP, the result is not significant as can be inferred from the graph shown in Figure 6c,d. The results obtained for the impact test are not in-line with the previously discussed results of both tensile tests of towpreg and tensile, flexural and short beam tests of the composites. This is due to the multidirectional nature of impact forces, whereas for all other tests, the application of the force was restricted in the direction either along the orientation of the fibers or perpendicular to it. Under multi-directional impact force, the composites show different type of behavior. UDC-FPFP as aforementioned is a sandwich structure, in which rings of flax fibers are separated by rings of relatively pp rich layer. On the application of the impact (Charpy or Izod) on such a sandwich structure, there is a tendency for the generation of the
Figure 6. (a) Flexural test results and (b) Short beam test results – for UDC-PFFP, UDC-FPFP, and UDC-FFPP (c) Charpy Impact column graphs and (d) Izod Notch Impact column graphs for UDC-PFFP, UDC-FPFP, and UDC-FFPP.

Table 4. Short beam, Charpy Impact, and Notch Impact test results of UDC-PFFP, UDC-FPFP, and UDC-FFPP obtained from friction spun towpreg unidirectional composites (n = 5).

| Sample                          | Interlaminar shear strength of friction spun towpreg Unidirectional Composites (UDC) | Charpy Impact Energy (J) | Notch Impact Energy (J) |
|---------------------------------|---------------------------------------------------------------------------------------|--------------------------|-------------------------|
| Friction spun towpreg Unidirectional Composites (UDC) | Short beam strength (MPa) $F_{bs} = 0.75 \times \frac{P_{m}}{h}$ (standard deviation) | Charpy Impact Energy (J) (standard deviation) | Notch Impact Energy (J) (standard deviation) |
| UDC - PFFP                      | 6.8 (±0.9)                                                                             | 2.3 (±0.4)               | 2.0 (±0.2)               |
| UDC - FPFP                      | 7.2 (±0.6)                                                                             | 1.4 (±0.1)               | 1.0 (±0.2)               |
| UDC-FFPP                        | 7.5 (±1.9)                                                                             | 1.8 (±0.1)               | 1.9 (±0.4)               |

This micro-crack generated at the interface propagates through the flax rich regions easily as these regions are resin starved relatively. Hence, UDC-FPFP has the lowest impact strength than UDC-FFPP and UDC-PFFP.
Conclusions

Friction spun towpregs with flax as reinforcement and polypropylene as matrix were produced with different radial positions such as PFP, FPFP, and FFPP. The produced friction spun towpregs were consolidated to yield unidirectional composites UDC-PFP, UDC-FPFP, and UDC-FFPP. The effect of varying the radial position of the reinforcement and matrix within the cross-section of the friction spun towpreg was investigated. The following are the conclusions of the study.

- Tensile properties: The tensile strength of towpregs of PFP configuration was higher than that of FPFP and FFPP. In towpregs, flax fibers positioned in the core or closer to the core tend to slide past each other due to lack of lateral pressure and do not resist the loading. On the other hand, when the towpregs are consolidated, the polypropylene layers melt and impregnate the flax fiber bundles. Hence, solidified UDC-FFPP showed the highest strength among the unidirectional composites.
- Towpreg FPFP, which behaves poorly under tensile loading, on consolidation in to unidirectional composites as UDC-FPFP, exhibits higher properties in tensile, flexural and short beam tests. UDC-FFPP shows higher tensile strength than UDC-FPFP and UDC-PFP as a result of parallel arrangement of flax fibers in the core bound by the polypropylene matrix. In composites with flax fibers occupying the outer radial position in both UDC-FPFP and UDC-PFP, the twist experienced by flax fibers results in diminished mechanical characteristics. These observations and conclusions are also supported by the micro-computed tomography (µCT) analysis.
- However, composite UDC-FPFP shows better impregnation of polypropylene matrix with flax fibers. Also, in the short beam tests, the fracture of the fibers and matrix occurs along a plane perpendicular to the flax fibers. No delamination of the layers are observed in UDC-FPFP unlike UDC-FPFP and UDC-PFP.
- In Charpy and notch impact tests, both UDC-FFPP and UDC-PFP show higher energy absorption than UDC-FPFP.
- Depending on the end-use requirement of the composite, friction spinning using DREF spinning machinery enables the production of hybrid yarns with differing structures. For the applications in which composite will be exposed to mostly tensile and flexural loads the hybrid yarn structure of FFPP will be the most suitable, whereas for the composite applications involving resistance to sudden shock (impact), the hybrid yarn structure of PFP should gain more applications.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

Vijay Goud [15] http://orcid.org/0000-0002-2461-749X
Ashraf Nawaz Khan [16] http://orcid.org/0000-0003-3996-8855
Alagirusamy Ramasamy [17] http://orcid.org/0000-0002-8835-7535
Apurba Das [18] http://orcid.org/0000-0002-8134-5064
Dinesh Kalyanasundaram [19] http://orcid.org/0000-0001-5127-4122
Ethical approval

We confirm that all the research meets ethical guidelines and adheres to the legal requirements of the study country. The research does not involve any human or animal welfare-related issues.

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