Advances in Natural Fibre Reinforced Thermoplastic Composite Manufacturing: Effect of Interface and Hybrid Yarn Structure on Composite Properties

Mahadev Bar, R. Alagirusamy and Apurba Das

Abstract Natural fibre reinforced thermoplastic composite materials are becoming very popular in the material community due to several advantages of natural fibre and thermoplastic polymer. The demand of stronger and better composite than the existing ones is also increasing simultaneously with their growing popularity. However, natural fibre reinforced thermoplastics have some disadvantages associate with the poor fibre-matrix interaction, short length of the natural fibres and high melt viscosity of thermoplastic resins. All these factors decrease the ultimate mechanical properties of the natural fibre composites. However, the surface treatment of natural fibres, use of low twisted yarn and hybrid yarn during composite manufacturing significantly improve the mechanical properties of the natural fibre composites. The scope of all three approaches in determining composites mechanical properties have been reviewed here. Finally, the combined effects of interface and DREF spun hybrid yarn structure on the tensile and flexural properties of flax-PP based unidirectional composite specimen have been discussed in this chapter.

Keywords Natural fibre · Interface · Biocomposite · Hybrid yarn

Introduction

Reduction of carbon footprint, global warming and climate changing are the major concern of the present world. Governments are encouraging the researchers as well as industries to invent and implement the environment friendly, ecologically sustainable development mechanisms to overcome these major climate related issues. Use of natural resources and recyclable thermoplastic matrices for composite manufacturing, fit well into this picture [1–9]. Beside this, use of natural fibre as

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composite reinforcing material has few more advantages over the glass and other synthetic fibres. For instance, natural fibres are abundantly available in every corner of the world at reasonable price. They have low density, high specific strength and stiffness with compare to glass and other synthetic fibres. Natural fibres also exhibit unique acoustic and thermal insulating property due to their hollow cellulosic structure. The production of natural fibre requires very less energy and it involves CO_2 absorption whilst returning oxygen to the environment. In other words, natural fibres are CO_2 neutral i.e. the combustion of natural fibre does not return excess CO_2 to the atmosphere. The production of natural fibre does not depend on the fossil resources and it does not promote the activities like sand mining (sand is the major raw material for glass fibre) which is one of the main reason of soil erosions. Moreover, the use of natural fibre develops a non-food agricultural based economy and creates job opportunities in the rural areas [4–10].

Like natural fibres, recyclable thermoplastic polymers are also getting more attention of the composite researchers as well as composite manufacturing industries. This is mainly due to several advantages of thermoplastic polymers over the thermoset polymers. For instance, thermoplastic polymers are non-corrosive in nature, have long self-life and shorter curing cycle. They are ductile in nature and can be repaired, recycled and reused as per requirement. In room temperature, thermoplastic polymers remain in solid form. Hence, during processing it does not contaminate the machine parts [6–10]. The pre-mentioned advantages of natural fibre and thermoplastic resin find several uses of natural fibre reinforced thermoplastic composite in different areas such as automobiles, constructions, households, sporting goods, packaging etc. [8–15].

Since, last few decades lot of research have been conducted on natural fibre composite and many research articles have been published addressing various challenges. Besides research institutions, many industries such as Libeco Lagae (Belgium), Lineo (Belgium) and NPSP (Netherlands) have shown their interest over natural fibre reinforced thermoplastic composites. In a recent survey, it is predicted that the market size for natural fibre composites will reach to \$5.83 billion by 2019 and it will continue with a compounded annual growth rate of 12.3% [16]. Along with this increasing market growth the demand of natural fibre based strong composites are also increasing exponentially [1–6].

However, natural fibre reinforced thermoplastics have some drawbacks. For instance, the poor fibre-matrix interaction which restricts the full strength utilization of natural fibre to the final composites. Secondly, natural fibres have short fibre length which make it difficult to control the fibre alignment into the composite structure. Unlike thermoset resins, thermoplastic resins have very high melt viscosity which restricts the even resin distribution into the composite structure and ultimately resulted in a composite with lot of void. The high viscous thermoplastic resin also promotes the fibre misalignment into the composite structure. All these factors diminish the mechanical performance of natural fibre composite [17–21]. Surface modification of natural fibre, use of low twist yarn and hybrid yarn during thermoplastic composite manufacturing can overcome these pre-mentioned shortcomings. Different shortcomings of natural fibre composites and their remedies are discussed in this chapter.

Interface Modification and Its Effect on Composite Properties

Natural fibres are hydrophilic in nature while thermoplastic matrices are hydrophobic in nature. Hence, the fibre and matrices are not compatible to each other. On the other hand, fibre-matrix interface plays an important role in determining the mechanical properties of the fibre reinforced composites. Because, the stress transfer from matrix to fibre is taking place across the interface. The poor or imperfect interface acts as a stress concentrator during mechanical testing [19–22]. Interfacial bonding between fibre and matrix can occur by means of four mechanism which are (i) mechanical bonding, (ii) electrostatic bonding, (iii) chemical bonding and (iv) reaction or inter-diffusion. In a good fibre-polymer interface, more than one force is acted at the same time and same interface [23].

Extensive research has been carried out, nevertheless research is still going on to improve the fibre-matrix bonding behavior of the natural fibre reinforced composite system [24–27]. The interfacial strength of a natural fibre composite system can be improved either by modifying the fibre surface or by modifying the matrix or by modifying the both. Among these methods, fibre surface modification is more effective than the matrix modification approach. Fibre surface modification to improve the fibre-matrix interaction can be largely divided into chemical approaches, physical approaches and biological approaches or enzyme treatment [1, 6–9]. The advantages and disadvantages of all three approaches have been discussed below.

Surface modification of natural fibre through chemical treatment is a very effective way of improving fibre-matrix interaction. There are several chemical treatment techniques available which can effectively modify the natural fibre surfaces. Among them, natural fibres surface treatment with alkali, MAgPP, saline coupling agent, benzyl, acryl, permanganate, peroxide, isocyanate are very well-known [1, 6–9, 19–22]. Alkali treatment removes the fat, wax, lignin and hemicellulose from the natural fibre surfaces. This makes the fibre surface rough and exposes the cellulose for interfacial bonding. Mild alkali treatment also improves the crystallinity and the breaking strength of the natural fibre [28–30]. While, the other chemicals except alkali are behaved as coupling agent. The one end of such chemicals is polar in nature while the other end is non-polar in nature. The polar end of the coupling agent reacts with the polar functional groups of the natural fibre while the non-polar end is entangled with the thermoplastic polymer chains. This phenomenon enhances the fibre-matrix interaction of the natural fibre composite system [25–28]. For example, MAgPP which can react with the hydroxyl groups present on the natural fibre surface through covalent bond

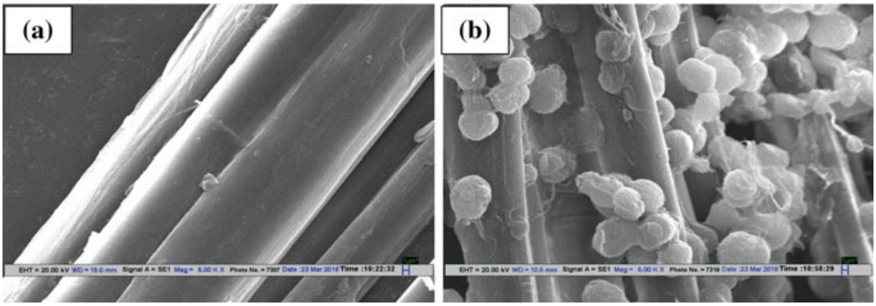


Fig. 1 SEM images of **a** untreated flax fibres, **b** MAgPP treated flax fibres

formation and forms a continuous layer of MAgPP around the natural fibre. Figure 1 shows the SEM images of untreated and MAgPP treated flax fibre. During composite manufacturing, the PP chains present on the fibre surface, adhere with the thermoplastic matrices.

It has been observed that the chemical treatment of natural fibre improves the tensile, flexural and other properties of the natural fibre composite. It has also been observed that among all methods of improving interfacial bond strength, the natural fibre treatment with MAgPP could be regard as most successful. It has been shown to give almost twice the composite strength as obtained with silane treatment [27].

Surface modification of natural fibre through chemical means successfully improves the interfacial bonding strength of natural fibre composite system. But, there are unresolved pollution problem related to disposal of chemicals after treatment. The cost of these chemicals is very high and most of them are health hazardous in nature [1, 6]. However, the physical approach of natural fibre surface modification does not have the pre-mentioned problems. Physical approach includes plasma treatment, corona discharge, electronic beam radiation, IR treatment, fibre beating etc. [1, 6–9, 24, 31]. Plasma is known as forth state of matter. It can be defined as partially ionized gases that have a collective ionized behavior. The main advantage of the plasma treatment is that it confines to the fibre surface only. It does not change the bulk properties of the material. The proper selection of starting compounds and external plasma parameters such as pressure, power and treatment time can create desire compound on the fibre surface [24]. Yuan et al. [32] have subjected wood fibre to the cold-plasma and Ar-Plasma treatment and produced wood-PP composite using the same. It is observed that the plasma treatment enhance the hydrophobicity and roughness of the wood fibre which significantly improves the tensile and flexural properties of the resultant composite. Corona is defined as a luminous, audible discharge that occurs due to inhomogeneous electrode geometries such as point electrode and plane. Compared to plasma, the corona discharges are relatively low power electrical discharge that takes place at atmospheric pressure. The corona discharge brings the chemical and physical changes of fibres including increasing surface polarity and roughness of the fibre. However, corona discharge is not so effective on three dimensional surfaces such as textile fabric [31, 32]. Belgacem et al. [33] have studied the effect of corona discharge on Cellulose-PP composite. It is observed that the composite strength improves when either one or both components are modified by corona discharge pretreatment. Electron beam radiation is another way of fibre surface modification. It improves the interfacial bonding between natural fibres and thermoplastic polymer by producing free radicals that encourage crosslinking [34]. The next physical approach of natural fibre surface modification is ultrasound treatment. Ultrasound is defined as very high frequencies of sound, above 20 kHz, generally used for medical and diagnostic purposes. Ultrasound treatment of natural fibre clean the fibre surface and make it rough, as a result it improves the fibre matrix interaction [31, 35].

Surface modification of natural fibre through biological means is another way of improving fibre-matrix interaction. Compared to chemical and physical approaches of natural fibre surface modification, the biological approach is quite new and advantageous [1, 6, 9]. In biological approaches natural fibres are treated with enzymes or fungi's. The biological treatment is environment friendly and have a focused performance. In general, the enzyme treatment removes hemi-cellulose and lignin from the fibre and makes the fibre surface rough. In addition, it also create holes on the fibre surface which helps in better interlocking with the matrix. Bledzki et al. [36] have studied mechanical properties of PP composite reinforced with enzyme treated abaca fibre. It is observed that the enzyme treatment enhances the fibre surface roughness as a result up to 45% improvement in composite tensile strength is observed. But, the enzyme treatment is time consuming and very specific to temperature and pH [1, 9].

Effect of Yarn Twist on Composite Properties

Composite materials are anisotropic in nature and exhibit maximum mechanical properties along the fibre direction [13]. Goutianos et al. [37] have reported that a woven fabric reinforced composite shows at least 3–4 time better mechanical properties than a nonwoven mat reinforced composite. Hence, it can be concluded that a composite will exhibit highest mechanical properties when the reinforcing fibres are completely aligned to the direction of applied load [38–40]. Effect of fibre orientation on composite properties is expressed by the rule of mixture equation:

$$E_c = \eta_0 \eta_l V_f E_f + \left(1 - V_f\right) E_m \tag{1}$$

where, E_f, E_m and E_c are the mechanical properties (modulus or failure strength) of the fibre, matrix and composite respectively, η_l is a factor related to fibre length, and η_0 is related to fibre alignment.

Unlike synthetic fibres, natural fibres have short fibre length. Hence, it is difficult to control these fibre alignment in a composite structure [41–43]. Textile yarns or yarn based textile structures can control the fibre orientation into the composite.

Yarn is a structure in which short staple fibres are twisted together. Twist enhances the cohesion between the fibres and holds the fibre together into the yarn structure. On the other hand, twist diminishes the maximum fibre strength utilization due to obliquity effect. At the same time, twist reduces the rate of production which enhances the ultimate cost of the yarn [43, 44]. In a composite structure fibres are held together by means of resin. Hence, once the composite is made, the yarn twist has no such importance. Goutianos et al. [37] have observed that low twisted yarn has low strength thus, it cannot be used in processes such as pultrusion or textile manufacturing routes like knitting or weaving. Therefore, it is concluded that the natural fibre based reinforcing yarn should have minimum level of twist which should allow it to process on textile machines.

Ma et al. [43] have manufactured sisal yarn reinforced phenol composite using sisal yarn of different twist level and have reported the effect of yarn twist on different composite properties. It is observed that high twisting level of the reinforcing yarn diminishes the mechanical properties of the resultant composite. A modified rule of mixture equation has been used in the same study to calculate the ultimate stress (σ_1) of the composite samples which are further compared with the experimental results. The modified rule of mixture equation is mentioned below.

$$\sigma 1 = \frac{(\mathrm{Vf} * \sigma \mathrm{f} * \mathrm{N} * \mathrm{Af} * \cos \theta \,\mathrm{mean}\ )}{\mathrm{Ay}} + \mathrm{Vm}\,\sigma \mathrm{m} \tag{2}$$

where, σ_f is the axial tensile strength of the yarn A_f and A_y is the cross sectional area of sisal fibers and sisal yarns respectively. N is the no of fibre in the yarn cross-section. θ_{mean} is a function of average twist angle at the yarn surface. V_f and V_m are the fibre and matrix volume fraction respectively. σ_m is the axial tensile strength of the matrix.

Hybrid Yarn and Its Effect on Composite Properties

In the arena of natural fibre composite, thermoplastic polymers are getting more interest due to their several advantages which are already discussed earlier. However, unlike thermoset resins thermoplastic polymer melts have very high viscosity. This high melt viscosity makes the even distribution of thermoplastic resin in the composite structure very difficult. This problem increases the void content in the resultant composite and ultimately leading to inferior composite properties [9, 18, 45]. Use of hybrid yarn during thermoplastic composite manufacturing can solve the above mentioned problems. Hybrid yarns are the yarn having more than one fibre component in its structure. The hybrid yarn used for thermoplastic composite manufacturing has both the reinforcing as well as matrix forming fibre components.

Based on yarn structure, hybrid yarns are of three types namely wrapped yarn, core spun yarn and commingled yarn [18]. In a wrapped yarn structure, thermoplastic filaments are wrapped around a core of reinforcing fibers while in core spun yarn structure, thermoplastic staple fibres are wrapped around the core of reinforcing fibre. Commingled yarns are produced via commingling process in which the reinforcing and matrix forming filaments are passed through a compressed air nozzle and mixed together. Among these hybrid yarn structures, commingled yarn provides the high potential for through mixing of matrix and reinforcing components. However, natural fibres have short fibre length thus, it is not suitable for commingling [46]. Natural fibre based core spun or wrapped yarn structure can be manufactured through different spinning techniques such as ring spinning, rotor spinning, DREF spinning, wrap spinning, micro-braiding etc. Alagirusamy et al. [18] have summarized different methods of hybrid yarn manufacturing and have explained their effectiveness on composite properties.

In general, hybrid yarn reduces the effective resin flow distance as a result the thermoplastic resin distribution into the composite structure is improved. George et al. [47] have developed a bio-commingled composite using PP filament and twisted jute yarn. Bio-commingling improves the wetting of reinforced natural fibre which ultimately results in superior composite property. A similar kind of result is observed in case of micro-braided hybrid yarn reinforced composite studies where the micro-braided yarn is prepared using twisted jute yarn as core and PP filament as sheath [48]. Although, micro-braiding and bio-commingling enhance the natural fibre reinforced composite properties by lowering effective resin flow distance but these methods are not commercially viable. Because, the rate of production of micro-braided yarn is very low and the bio-commingling method is suitable for producing small and simple structures only.

Composites with Low Twisted Core Based Hybrid Yarn with Modified Interface

So far, the hybrid yarns for natural fibre composite reinforcement have a twisted core made of natural fibres. In most of these studies, the core natural fibres are not subjected to any surface modification. In this part of the present chapter, the combined effect of natural fibre surface modification and the hybrid yarn structure on composites tensile and flexural properties have been discussed. Hence, Flax-PP based core-sheath structured hybrid yarns are manufactured through DREF spinning method. During DREF spinning, yarn parameters such as core yarn twist and sheath percentage are varied at three different levels i.e. 0.72, 4.42, 8.12 TPI; and 40, 50, 60% respectively. Before hybridization, flax yarns are treated with MAgPP and depending on the experimental design MAgPP treated or untreated flax yarns are fed as core during DREF spinning. In this way, total 10 sets of hybrid yarn have been manufactured. The details of the produced hybrid yarn parameters are tabulated in Table 1.

Table 1 The details of hybrid yarns used for composite manufacturing

Untreated flax core		MAgPP treated flax core	
Core twist (twists/in.)	Natural fibre percentage	Core twist (twists/in.)	Natural fibre percentage
0.72	40	0.72	40
	50		50
	60		60
4.42	60	4.42	60
8.12	60	8.12	60

These hybrid yarns are further consolidated in a compression molding machine to manufacture unidirectional composite samples. These composite samples are then tested for tensile and flexural performances. The test results are analyzed critically and are reported below accordingly.

The stress-strain curves of different untreated as well as MAgPP treated flax reinforced composite samples are presented in Figs. 2 and 3 respectively. The photographs of tensile failure surfaces of untreated and MAgPP treated flax core based hybrid yarn reinforced unidirectional composite specimens are shown in Fig. 4 and in Fig. 5 respectively. The photographs reveal the manner in which composite specimens fail in tensile tests. In case of untreated flax yarn reinforced composite specimens and twisted, MAgPP treated flax yarn reinforced composite specimens, the failure is rather dominated by shear due to poor interfacial bonding between the fibres and matrices. It can also be predicted that in the above mentioned

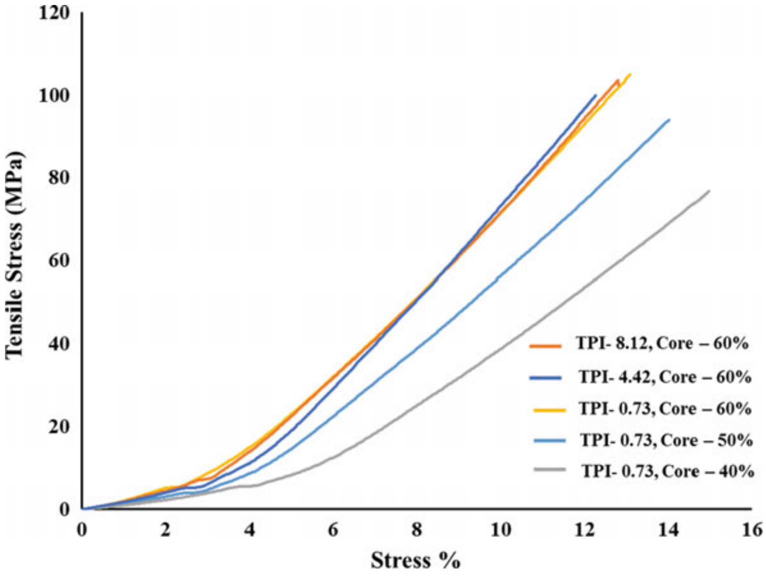


Fig. 2 Stress-strain curves of untreated flax core based hybrid yarn reinforced composite samples

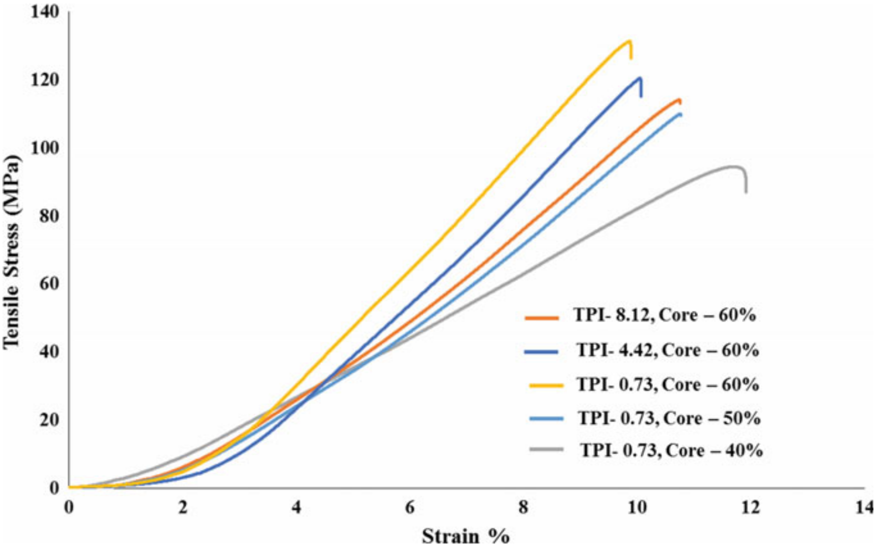
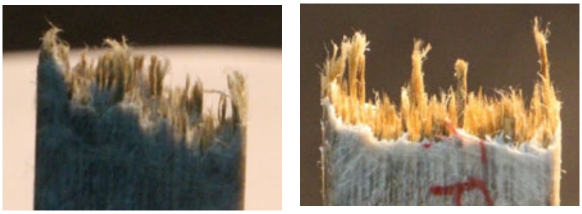


Fig. 3 Stress-strain curves of MAgPP treated flax core based hybrid yarn reinforced composite samples

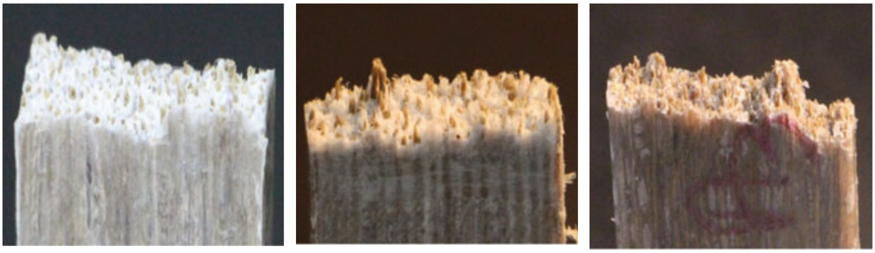
TPI- 0.73; C: S ratio- 40 : 60 **TPI- 0.73; C: S ratio- 50 : 50** **TPI- 0.73; C: S ratio- 60 : 40**



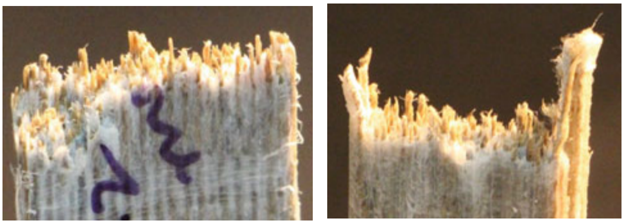
TPI- 4.42; C: S ratio- 60 : 40 **TPI- 8.12; C: S ratio- 60 : 40**

Fig. 4 Photographs of tensile failure ends of untreated flax core based hybrid yarn reinforced unidirectional composites

cases, the matrix failure occurs first then fibre slippage become more dominant. This resulted in tensile failure composite ends with lot of pulled out fibres. The photographs of tensile failure composite samples also state that the fibre pullout length decreased significantly with decreasing flax yarn twist and with decreasing



TPI- 0.73; C: S ratio- 40 : 60 **TPI- 0.73; C: S ratio- 50 : 50** **TPI- 0.73; C: S ratio- 60 : 40**



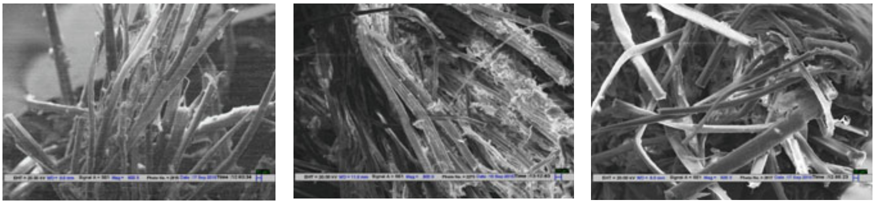
TPI- 4.42; C: S ratio- 60 : 40 **TPI- 8.12; C: S ratio- 60 : 40**

Fig. 5 Photographs of tensile failure ends of MAgPP treated flax core based hybrid yarn reinforced unidirectional composites

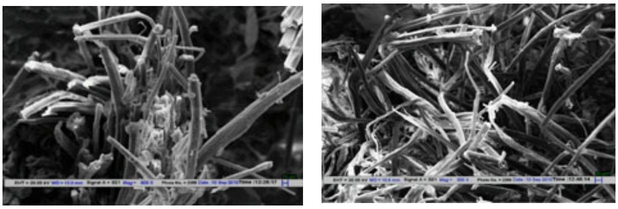
flax content into the composite. High twist reduces the resin penetration into the structure of yarn. The molten resin penetration into the fibre bundle is less when the composite is manufactured with low resin content. Hence, the resin distribution into the composite structure hinders significantly with increasing flax content and flax yarn twist.

MAgPP treatment of flax fibres improves the fibre-matrix bonding as a result the length of pulled out fibres decreases significantly after the MAgPP treatment of flax fibres. However, no fibre pull out at the tensile failure end is observed, in case of low twisted, MAgPP treated flax reinforced composites. It seems that in the above mentioned cases the fibre and matrix both behave as one unit and fail together almost in a straight line. While in all other cases the line of failure is an inclined curvy line.

SEM images of tensile fracture ends of untreated and MAgPP treated flax core based hybrid yarn reinforced composites are shown in Figs. 6 and 7 respectively. SEM images reveal that the molten PP does not penetrate into the highly twisted flax yarn structure. In case of partially untwisted flax yarn reinforced composites, the resin penetrates into the yarn surface layer only while the yarn core remains dry. Complete wetting of flax yarns are observed in case of low twisted flax yarn reinforced composite. Lot of fibre pull out is observed in the SEM images of untreated flax yarn reinforced composites and MAgPP treated, twisted flax yarn reinforced composites. While, in case of MAgPP treated, untwisted flax yarn reinforced composites no fibre pullout is observed due complete wetting of thermoplastic fibres and improved bonding between the fibres and matrices.

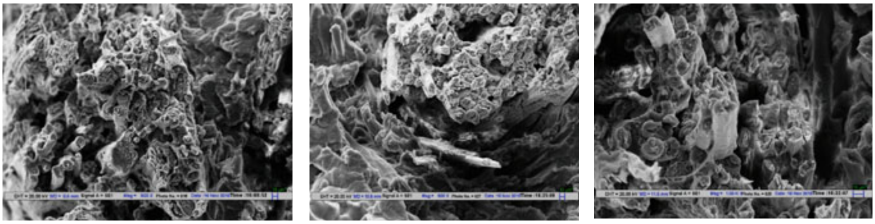


TPI- 0.73; C: S ratio- 60 : 40 TPI- 0.73; C: S ratio- 50 : 50 TPI- 0.73; C: S ratio- 40 : 60

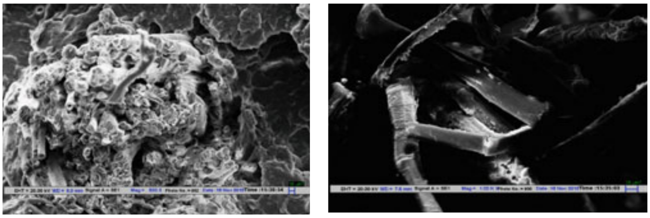


TPI- 4.42; C: S ratio- 40 : 60 TPI- 8.12; C: S ratio- 40 : 60

Fig. 6 SEM images of untreated flax core based hybrid yarn reinforced, tensile fracture composite ends



TPI- 0.73; C: S ratio- 60 : 40 TPI- 0.73; C: S ratio- 50 : 50 TPI- 0.73; C: S ratio- 40 : 60



TPI- 4.42; C: S ratio- 40 : 60 TPI- 8.12; C: S ratio- 40 : 60

Fig. 7 SEM images of MAgPP treated flax core based hybrid yarn reinforced, tensile fracture composite ends

Maximum tensile stress and the modulus of the MAgPP treated and untreated flax core based hybrid reinforced unidirectional composite samples are graphically presented in Fig. 8 and in Fig. 9 respectively. Flax fibres are the prime load bearing components of the flax-PP based hybrid yarn reinforced unidirectional composite. The fibre-matrix interface becomes stronger after the MAgPP treatment of flax

Fig. 8 Maximum tensile stress of the hybrid reinforced unidirectional composites

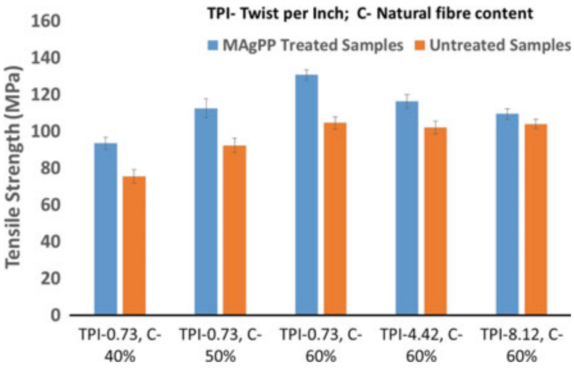
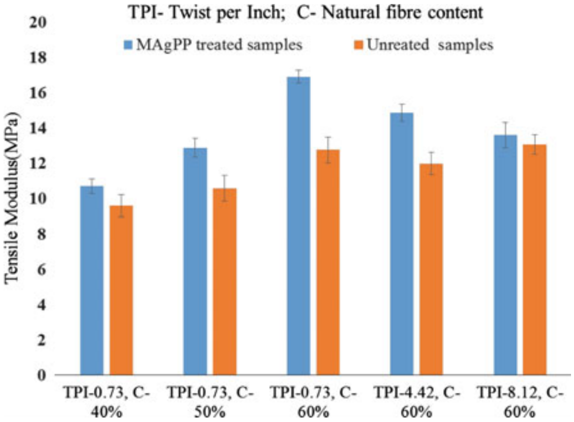


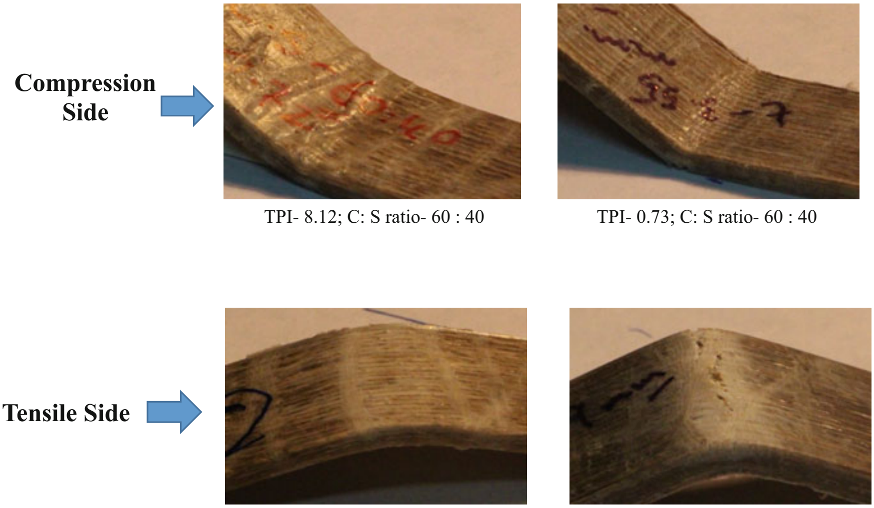
Fig. 9 Tensile modulus of the hybrid reinforced unidirectional composites



fibre [20, 21]. Hence, up to 25% improvement in the tensile strength and up to 33% improvement in tensile modulus of the unidirectional composites are observed after the MAgPP treatment of reinforcing flax yarns. Similar results are experienced in case of increasing flax fibre content from 40 to 60% in the composite structure. Low yarn twist enhances the fibre orientation in the composite structure. However, it does not exhibit any significant influence on the tensile strength and modulus of the untreated flax yarn reinforced unidirectional composites due to poor interfacial performance. On the other hand, around 20% improvement in tensile strength and 25% improvement in tensile modulus are observed while the reinforcing untwisted yarns are treated with MAgPP. This is mainly the result of improved fibre-matrix interaction and improved resin distribution into the composite structure.

Flexural strength and modulus of the flax-PP based hybrid yarn reinforced composite samples are tested according to three point bending test method. During three point bending test, one side of the composite specimen is subjected to a compressive force while the other side is subjected to the tensile force. The photographs of tensile and compression side of the untreated and MAgPP treated flax core based hybrid yarn reinforced unidirectional composite specimens are presented in Figs. 10 and 11 respectively. The photographs show that, after 3-point bending tests, PP matrix is accumulated on the compression side and no fracture is observed on the tensile side of the high twisted, untreated flax core based hybrid yarn reinforced unidirectional composite.

Few kinks on the compression side and some line of fracture on the tensile side are observed in case of low twisted, untreated flax reinforced composite and highly twisted, MAgPP treated flax reinforced composites. However, no matrix accumulation or kinks on the compression side and a sharp line of fracture on the tensile side of the MAgPP treated, low twisted flax reinforced composite are observed. The flexural stress-deformation curves of untreated and MAgPP treated composite samples are shown in Figs. 12 and 13 respectively. It is observed that the MAgPP treated composite samples have reached to a maximum stress level, then it experienced a sharp fall. After that, it continues to take load for a certain deflection and then it fails. On the other hand, untreated, twisted flax yarn reinforced composite reaches to a maximum stress level and then gradually fails after experiencing some deflection. However, a sharp fall after reaching the maximum stress is observed in case of low twisted, untreated flax yarn reinforced composite. It can be concluded that the interfacial strength is better in case of MAgPP treated flax yarn reinforced samples than the untreated one. Hence, the MAgPP treated flax yarn reinforced composites and low twisted, untreated flax yarn reinforced composites show a sharp fall in the flexural stress-deformation curves due to better interphase. On the other hand, due to poor interface no such sharp fall in the flexural stress-deformation curve of the untreated, twisted flax yarn reinforced composite is observed.



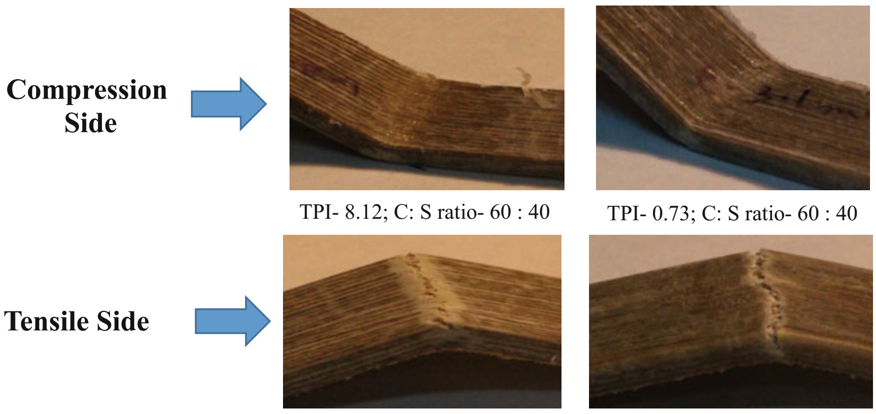
TPI- 8.12; C: S ratio- 60 : 40

TPI- 0.73; C: S ratio- 60 : 40

TPI- 8.12; C: S ratio- 60 : 40

TPI- 0.73; C: S ratio- 60 : 40

Fig. 10 The photographs of untreated flax core based hybrid yarn reinforced, 3-point bending tested unidirectional composite specimens



TPI- 8.12; C: S ratio- 60 : 40 TPI- 0.73; C: S ratio- 60 : 40

TPI- 8.12; C: S ratio- 60 : 40 TPI- 0.73; C: S ratio- 60 : 40

Fig. 11 The photographs of MAgPP treated flax core based hybrid yarn reinforced, 3-point bending tested unidirectional composite specimens

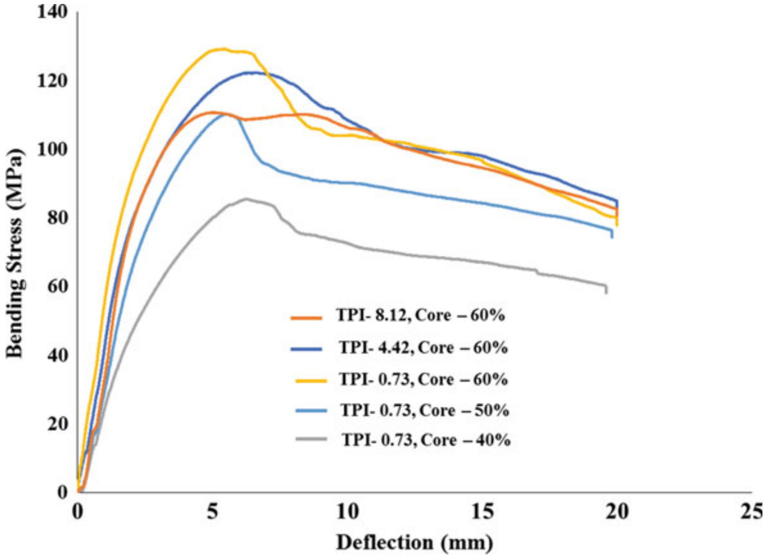


Fig. 12 Bending stress-deflection curves of untreated flax core based hybrid yarn reinforced composite samples

From the previous observations, it can also be concluded that the failure of high twisted, untreated flax core based hybrid yarn reinforced unidirectional composites is mainly dominated by the compressive force during 3 point bending tests. The combined action of tensile and compressive forces dominates in case of low twisted, untreated flax core based hybrid yarn reinforced composites and high

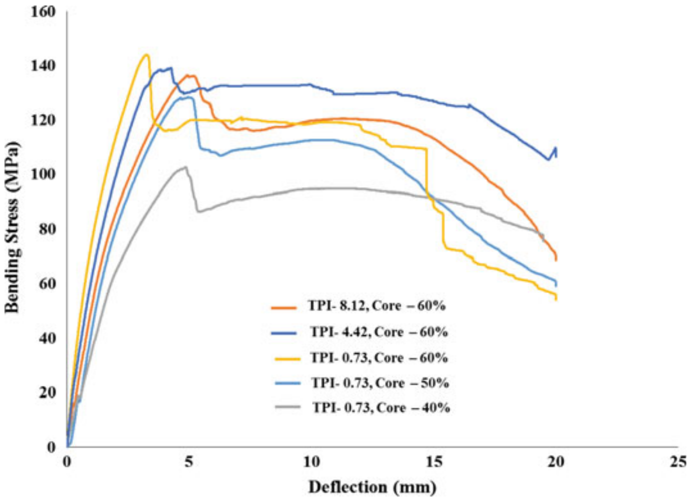


Fig. 13 Bending stress-deflection curves of MAgPP treated flax core based hybrid yarn reinforced composite samples

twisted, MAgPP treated flax core based composites. Tensile forces mainly dominate during the 3-point bending failure of low twisted, MAgPP treated flax reinforced composite samples.

Figures 14 and 15 represent the flexural strength and modulus values of the hybrid yarn reinforced unidirectional composite samples. It is observed that 40% improvement in tensile strength and 70% improvement in tensile modulus is experienced while the flax fibre content in the composite increases from 40 to 60%. However, up to 20% improvement in flexural modulus and 7% improvement in flexural strength are observed after the MAgPP treatment of core flax yarn. Similar

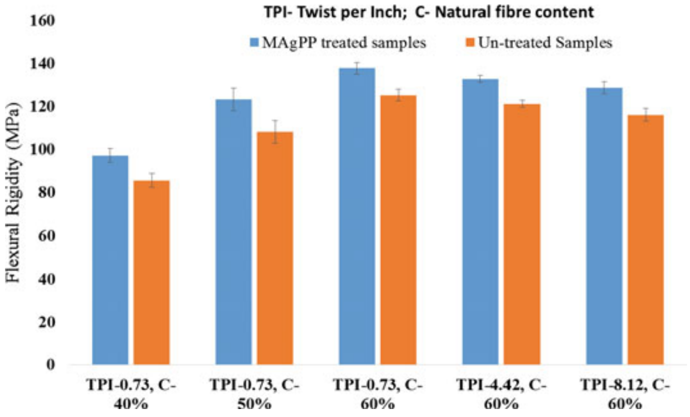


Fig. 14 Flexural rigidity of the hybrid reinforced unidirectional composites

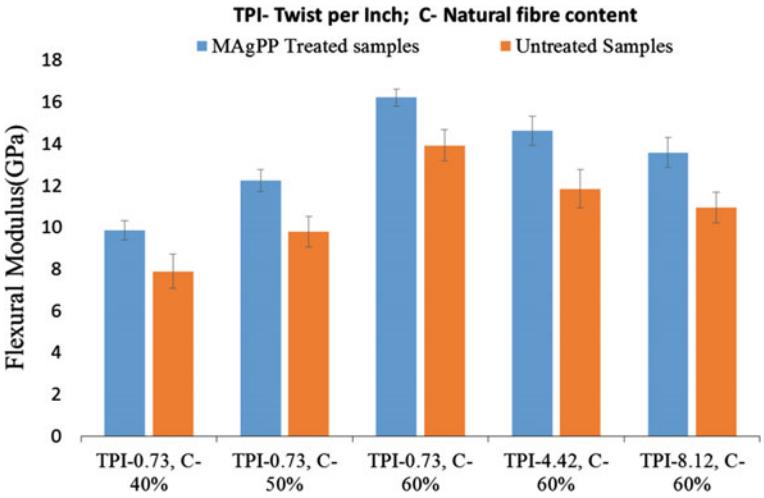


Fig. 15 Flexural modulus of the hybrid reinforced unidirectional composites

changes are experienced while the flax yarn twist is decreased from 8.12 TPI to 0.73 TPI. In this present composite system, flax fibres are the main load bearing components and after the MAgPP treatment of flax fibres the fibre-matrix interface become stronger. Hence, the flexural strength and modulus of the composite samples increase after MAgPP treatment of flax yarn and with increasing flax fibre content into the composite structure. Yarn twist of the reinforced flax yarn decreases the alignment of the reinforced flax fibres into the composite structure and it also restricts the PP resin distribution into the composite. Hence, flexural strength and modulus of the composite samples increase with decreasing reinforced flax yarn twist.

Conclusions

In this chapter, the individual as well as the combined effect of interface, yarn twist and hybrid yarn structure on the natural fibre reinforced thermoplastic composite have been discussed. It is observed that low yarn twist and high matrix content improve the resin distribution into the composite structure. Surface modification of the natural fibre improves the fibre-matrix interaction. Hence, the tensile and flexural properties of the unidirectional composite enhance after the surface treatment of natural fibre and with decreasing yarn twist and with increasing natural fibre content.

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