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Multi-scale analysis of flax fibres woven fabrics for composite applications

A C Corbin[1]*, D Soulat[1], M Ferreira[1], A R Labanieh[1], X Gabrion[2], V Placet[2]

[1] ENSAIT, GEMTEX – Laboratoire de Génie et Matériaux Textiles, F-59000 Lille, France, 2 allée Louise et Victor Champier BP 30029 59056 Roubaix Cedex 1 France
[2] FEMTO-ST, CNRS/UFC/ENSMM/UTBM – Université de Bourgogne Franche-Comté 24 rue de l'Epitaphe 25000 Besançon France

* anne-clemence.corbi@ensait.fr

Abstract. Natural fibres are used as an alternative to man-made fibres in fibre reinforced composite materials in a variety of applications due to their good specific strength and stiffness properties and limited environmental impact. However, contrary to man-made fibres, used in the form of continuous filaments, natural fibres are extracted from plants in which they have a finite length. After their extraction form plants, they are paralyzed and twisted together to form roving or yarn. In this paper, the potential of manufacturing flax woven reinforcements optimized for composite applications is evaluated. A multi-scale analysis of the textile and mechanical properties is conducted to evaluate the impact of each transformation step and the respective contribution of fibre, yarn and fabric to the composite performance. The impact of a chemical treatment on the roving features is evaluated. Results show that this treatment doesn't impact significantly the fibre tensile strength and stiffness and improves its weavabilty. The difference between yarn and roving is also shown regarding the weavability and their impact on the composite tensile properties. The properties of these flax reinforced composites are finally compared with those available in the open literature for similar fibre composites. A promoting conclusion is then proposed.

1. Introduction

Nowadays, composite materials are more and more used to replace traditional materials, such as metals, ceramics or wood, due to their better specific properties. The organic matrix composite materials are made up of a reinforcement phase, and a matrix phase consisting of thermoplastic or thermosetting polymer. The carbon, glass and aramid fibres are the dominant fibres used as reinforcement. However, these fibres are expensive, difficult to recycle non-biodegradable and their handling and use can be dangerous for human health. A weak point of the glass fibre is also is quite high density. So, the plant fibre represents a promising eco-friendly alternative to the man-made fibres for textile reinforcement. However, they have with counterpart a lower resistance to temperature (which limits the level applied in several composite manufacturing processes), lower mechanical properties, an important moisture absorption capability and a year-to-year variability [1]. By contrast, the multi-scale analyses have shown that composite materials with natural fibre reinforcements have a variability in properties similar to those with carbon or glass reinforcements [2]. Thus, by using biobased reinforcement and matrix, the environmental impact, weight and cost of composite can be reduced and the thermal and acoustic properties improved [3]. Table 1 presents the specific gravity, specific strength, specific stiffness and strain at failure for flax and hemp fibre in comparison with glass and carbon fibre.

Table 1. Properties of several fibres commonly used in composite materials [4].

Fibre	Specific gravity ($g.cm^{-3}$)	Specific strength ($MPa.cm^3.g^{-1}$)	Specific stiffness ($GPa.cm^3.g^{-1}$)	Strain at failure (%)
Flax	1.45	550 – 1030	38 – 52	1.5 – 2
Hemp	1.48	370 - 600	27 – 44	1.6
Glass	2.55	780 – 940	27 – 29	3
Carbon	1.8	1900 - 2700	128	1.5 – 2.1

Currently, plant fibres are used for the manufacturing of reinforcements in form of chopped fibres nonwoven preforms and in the form of long fibres for UD preforms. But they are not commonly used in form of yarn or roving to manufacture woven fabric reinforcements that are optimized for composite applications. Only few studies report the behaviour of composite materials reinforced by woven fabrics [5,6]. In these works, the reinforcements were not necessarily well optimized for composite applications. With a multi-scale analysis, the parameters and properties of rovings, yarns, fabrics and composite can be optimized to obtain the better material which fits well with the requirements for this application. Plant fibres have a finite length. Therefore the spinning of the fibres is required after extraction from the plants, to paralyse and assembly the discontinuous fibres in a continuous reinforcement. A specific linear density is associated with the yarns. On the other side, the man-made fibres, such as glass or carbon, are produced under the form of filament (continuous fibre), so this spinning step is not needed. Assembling the fibres to form a roving or a yarn is carried out by twisting the fibres together to increase the inter-fibre friction or by gluing the fibres using a chemical agent. The twisting step has an impact on composite manufacturing and quality, because it can decrease the impregnation ability of yarns. Indeed, as the twist level increases, the yarn structure becomes more compact [7]. The twist level for roving is lower than that for yarn and a chemical treatment can be performed to impart the necessary resistance to the roving for weaving process. Different chemical treatments can be applied but they may have an impact on the internal structure of the fibres and on their mechanical properties [8]. The weaving process consists in warping yarn into a beam, installing the warp yarns under tension on the weaving loom then inserting a weft yarn successively though a shed created by raising and falling downward warp yarns alternately during the process according to weave pattern. Thus all these steps require sufficient strength and strain at failure for yarn and roving [9]. Therefore the potential of using roving to manufacture reinforcement by weaving process is examined in this paper and the impact of the use of chemical treatment is evaluated by conducting a multi-scale analysis and characterization up to the composite scale.

2. Materials and methods

Flax fibre in the form of two different half-products were used to manufacture different woven fabric reinforcements, namely yarn (Y) and roving without chemical treatment (R1) and with chemical treatment (R2) (Figure 1 (a), (b) and (c)). These yarns and rovings were provided by Linificio Canapificio Nazionale, an Italian Company.

Woven fabrics are produced on a manual dobby loom, a Leclerc Weavebird loom. Two plain weave fabrics are manufactured with 6 warps and 6 wefts per cm. For the first fabric (FLAX1), Figure 1 (d), yarn (Y) is used in warp and roving R1 in weft. While for the second fabric (FLAX2), Figure 1(e), yarn (Y) is also used in warp but roving R2 is used in weft. Weaving process requires applying high tension on warps (ends) during weaving that cannot be sustained by a roving. That is why yarn is used for the two fabrics in the warp direction. These produced fabrics are used to manufacture a composite with 4 plies using an epoxy resin, the GreenPoxy 56, provided by Sicomin. The composite is manufactured by thermocompression. It is cured at 130°C during 1 hour under a pressure of 3 bars. The fibre volume fraction of the obtained composite is approximately 45%. After manufacturing, the plates were stored in climatic chamber (T = 23°C, RH = 50%).

A multiscale analysis is conducted at each manufacturing stage in order to evaluate the impact of each stage on the reinforcement and composite properties, as well as the effect of the chemical treatment of roving (R2) on composite behaviour. Therefore, the properties of the materials are characterized at each scale: fibre, yarn, fabric and composite.

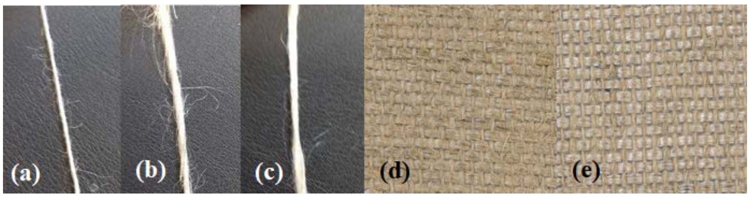

Figure 1. Pictures of yarns and fabrics: (a) Y yarn (b) R1 roving (c) R2 roving (d) F1 fabric (e) F2 fabric.

2.1. Fibre scale

The tensile properties of the flax fibres are identified by inverse method using the Impregnated Fibre Bundle Test (IFBT). Bensadoun and al. [10] have shown that IFBT method is a reliable and efficient method to determine the tensile properties of plant fibres, in particular when compared to the time-consuming and challenging single fibre tensile test (NF T25-501-2 standard [11]). To manufacture the IFBT specimens, bunches of roving were impregnated in an epoxy resin, the GreenPoxy 56, and cured at 60°C during 24 hours under a pressure of 2 bars. After manufacturing, the IFBT specimens were stored in a climatic chamber (T = 23°C, RH = 50%) during at least three weeks, to ensure that the composite material reaches the moisture equilibrium.

Tensile tests were further performed using a universal tensile electro mechanical machine (MTS Criterion 45) under a constant crosshead displacement rate of 1 mm/min and with a load cell of 5 kN full range. Fibre strength and stiffness were then determined by inverse method, using the rule of mixture and the recorded tensile stress-strain curves. The disorientation of the fibre, when compared to the longitudinal direction of the IFBT specimens, due to their twisting, is neglected, since twist level of the used rovings is very low.

2.2. Yarn scale

The textile and tensile properties of yarn and roving (R1 and R2) are also evaluated. For the textile properties, the linear density and twist level are measured according to NF G07-316 standard [12] and NF G07-079 standard [13] respectively. As well as the uniformity, hairiness index (H) and standard deviation of hairiness (sH) for the yarn and roving are measured via an Uster Tester machine. The uniformity is represented by the coefficient of variation of the weight or fibre number over the yarn length (CVm%). The hairiness index represents the total length of the protruding fibres with reference to the sensing length of 1cm of the yarn/roving.

The tensile test is also performed on a tensile machine, according to NF EN ISO 2062 standard [14] for a single yarn. In order to eliminate the effect of the sample length when comparing the tensile behaviour of a single yarn to the tensile behaviour of a yarn in the fabric structure, the same sample length of 200 mm is considered for both yarn and fabric samples in the tensile tests. The extension rate is set to 200 mm/min and a preload of 0.5 cN/Tex is applied for the yarn whereas no preload is applied for the roving. For each tensile test, the tenacity-strain curve is recorded. The tenacity of a yarn is defined as the force per linear density (Tex). These characterizations are conducted on yarns from the bobbins before weaving and on yarns extracted from the woven fabrics after weaving process.

2.3. Fabric scale

The textile and mechanical properties are also identified at the fabric scale. The thickness, areal density and air permeability are measured for both FLAX1 and FLAX2 according to NF EN ISO 5084 standard [15], NF EN 12127 standard [16] and NF EN ISO 9237 standard [17] respectively. The shrinkage percentage of warp and weft inside the fabric structure are also measured for both fabrics according to the NF ISO 7211-3 standard [18]. The bending and tensile behaviour are also characterized. A bending test is performed using a cantilever apparatus according to the ISO 4604 (05) standard [19], with a sample size of 300 length and 50 mm width. The tensile tests are performed according to the NF EN ISO 13934-1 standard [20] on a tensile machine, with an extension rate of 20 mm/min, gauge length of 200 mm, width of 50 mm and pre-tension of 5N. Sandpaper strips are glued to the jaws of the tensile machine clamps to improve gripping and avoid sample slippage. The force-displacement curve is recorded to calculate the breaking tenacity and strain at break.

2.4. Composite scale

The composite samples are manufactured using 4 plies of the flax fabrics and the GreenPoxy 56 epoxy resin, which is also used in IFBT tests. The impregnated reinforcements are cured during 1h at 130°C under a pressure of 3 bars. Tensile specimens were laser cut from the plates. The tensile test is performed on the composite samples according to NF EN ISO 527 standard [21], with a crosshead displacement-rate of 1 mm/min, a gauge length of 150 mm, a sample width of 15 mm and a sample thickness of 1.7 mm. The strength, tangent modulus (between 0% and 0.1% of strain) and strain at break are calculated from the recorded force-displacement curves. The identified properties of the manufactured composites are also compared with the properties of similar woven fabrics composites reported in the literature [5] and available on the market.

3. Results and discussion

3.1. Fibre scale

The specific strength and modulus of the fibres, back-calculated from IFBT, are listed in Table 2. The modulus 1 is calculated between 0% and 0.1% of tensile strain while modulus 2 is calculated between 0.3% and 0.5% of strain. Fibres without treatment come from R1 rovings and fibres with treatment comes from R2 rovings. Interestingly, Table 2 shows that the specific strength and modulus of the fibres, treated or not, are similar. A maximum difference of about 8 % on the mean values is observed. Thus, it can be concluded that the chemical treatment has no significant impact on the fibre tensile properties. As already observed for natural fibre [22], the first modulus is higher than the second one. In comparison with glass fibre, (properties in Table 1) flax fibre has a lower specific strength but it has a similar specific modulus. It confirms, once more, the interest of using the natural fibres like flax as a substitute to glass fibre in fibre reinforced plastic composite.

Table 2. Properties of flax fibres (back-calculated from IFBT method).

Fibre	Specific gravity ($g.cm^{-3}$)	Specific strength ($MPa.cm^3.g^{-1}$)	Specific modulus 1 ($GPa.cm^3.g^{-1}$)	Specific modulus 2 ($GPa.cm^3.g^{-1}$)
Flax fibres without chemical treatment (from R1 roving)	1.45 [4]	355 ± 21	35.2 ± 2.1	23.9 ± 0.7
Flax fibres with chemical treatment (from R2 roving)	1.45 [4]	377 ± 22	38.7 ± 2.8	21.4 ± 1.4

3.2. Yarn scale

The measured textile properties of the yarn (Y) and rovings (R1 and R2) are listed in Table 3. Their tensile behaviour is presented in Figure 2 through tenacity-strain curves. The yarn has a lower linear density than the roving, which is related to the lower number of fibres in its cross section. Therefore a higher twist level is generally inserted to the yarn. By twisting operation, the fibres take a spiral path in the yarn structure resulting in an increase of the inter-fibre compression and friction. That leads to a superior breaking tenacity and modulus when compared to the rovings (R1 and R2), as it can be seen on Figure 2. So, on the weaving loom, a high twist level is required for the warp yarn to decrease the breakage and to sustain the necessary applied tension during weaving. However, the angle between the fibre and yarn main directions (i.e. the spiral angle) increases with increasing twist level, which can be detrimental for the longitudinal tensile strength and rigidity of UD composites. Furthermore, when the twist level increases the fibres are compressed and the yarn structure is more compacted. Thus, the interpenetration of the resin inside the yarn may be more difficult and result in higher void volume fraction inside the yarn. Conversely, twisting leads to a decrease of the hairiness index (H) of the yarn when compared to the roving (R1 and R2) which have a lower twist level. It can also be noticed that the yarn is more irregular (CVm%) than the rovings (R1 and R2). This is related to the spinning process conditions.

By comparing the two rovings (R1 and R2), it can be concluded that the chemical treatment induces a decrease in the linear density. This is attributed to the removal of impurities and of some of the fibres during the treatment. Even though this treatment leads to a slight decrease in the hairiness index, it nevertheless induces an increase in the standard deviation (sH).

Table 3. Textile properties of yarns.

	Flax yarns (Y)	Flax rovings without chemical treatment (R1)	Flax rovings with chemical treatment (R2)
Linear density (Tex)	173.4 ± 14.1	369.8 ± 48.8	304.4 ± 16.7
Twist level (turns/m)	231.1 ± 17.8	31.6 ± 2.5	35.7 ± 3.7
CVm% (%)	27.9	18.8	20.0
Hairiness H	7.4	21.9	18.8
sH(%)	3.4	7.8	8.5

Thus, even if, the chemical treatment doesn’t have a significant impact on the textile properties of the roving, it induces, on the other hand, an obvious improvement in the breaking tenacity and stiffness. No significant change in the strain at break was observed (see Figure 2 (b)). Figure 2 (a) points out that the tangent modulus of the roving after treatment is close to the modulus of the yarn. So the treatment, even if inducing no significant effect at the fibre scale, induces an improvement of the tensile properties at the yarn scale (Figure 2. (b)). This is attributed to an increase in the cohesion at the interface between the fibres inside the yarn. Anyways, despite this hypothetical increase in cohesion, friction between fibres does still exist, since no impact is observed on the strain at failure of the yarns.

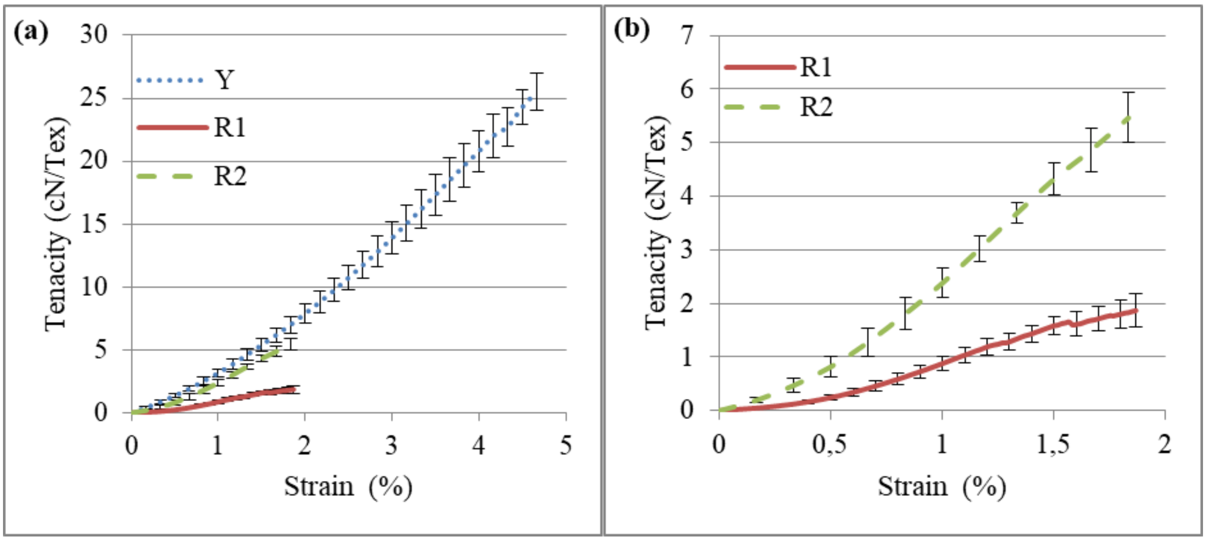

Figure 2. Tenacity vs. strain curves (a) Comparison of the 3 types of yarns and rovings (b) Zoom on rovings.

3.3. *Fabric scale*

The weavability of both rovings (R1 and R2) is evaluated for the two fabrics (FLAX1 (F1) and FLAX2 (F2)) by considering the number of breakage of the roving during the weaving process. 50% of roving R1 (without treatment) breaks by the weft insertion operation during weaving against less than 1% for R2 (with treatment). Thus, the chemical treatment of the roving permits to decrease the material waste: from 15% without treatment to only 3% with treatment. As a conclusion, the chemical treatment improves the roving behaviour during weaving process by sticking the fibres to the roving body accompanied with a lower hairiness index (Table 3). It finally results in a reduction of the rubbing damage caused by passing the roving over loom machineries and by yarn/roving contact.

The textile properties of the manufactured fabrics F1 and F2 are listed in Table 4. The bending rigidity values and tenacity-strain curves are presented in Figure 4 (a and b).

Table 4. Textile properties of fabrics.

	Thickness (mm)	Areal density (g/m²)	Air permeability (L/m²/g)	Warp shrinkage (%)	Weft shrinkage (%)
FLAX1 (F1)	1.00 ± 0.07	307.66 ± 9.20	1364.90 ± 253.59	2.72 ± 0.33	1.90 ± 0.18
FLAX2 (F2)	0.91 ± 0.03	288.43 ± 19.82	1934.60 ± 218.68	2.98 ± 0.25	2.56 ± 0.40

The thickness and the areal density of F1 are slightly higher than those of F2. This is related to the lower linear density of the roving R2, which is more compacted, as pointed out in Table 3. It also impacts the air permeability. A higher permeability index is measured for F2 when compared to F1, even if an identical warp and weft count per unit length and a yarn (Y) count are considered for both fabrics.

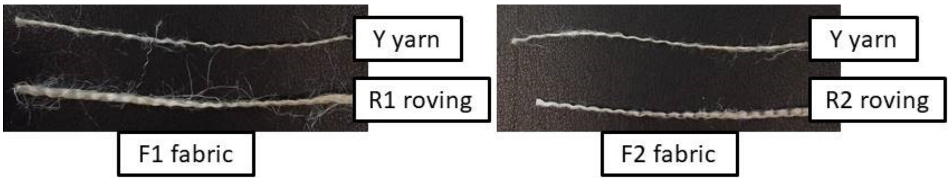

Figure 3. Visual aspect of yarns extracted from the fabrics

The weave diagram is the same for the two fabrics, it is a plain weave. In table 4, it can be observed that the warp shrinkage is more important than the weft shrinkage. This is due to the manufacturing process settings, in particular the yarn tension and the shed formation, in addition to a lower linear density for the yarn making it more flexible to bending when compared to roving. In F2 fabric, weft yarns (R2) are more compact and more rigid than R1 in F1 fabrics. Thus, warp and weft yarns in F2 are more crimped than in F1 and warp and weft shrinkages are higher in F2 than in F1 (Figure 3).

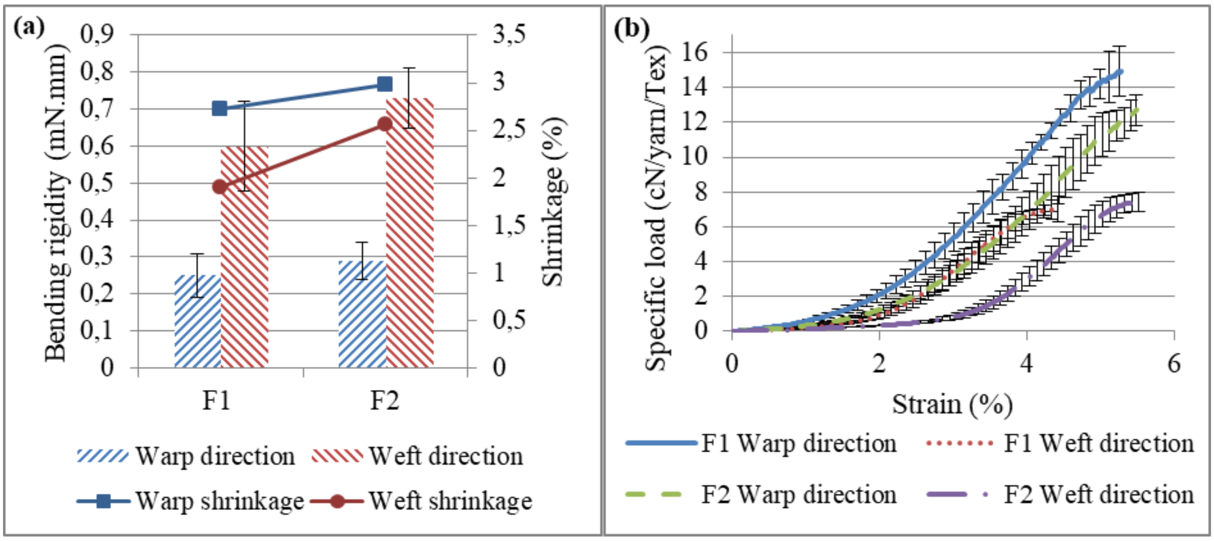

Figure 4. Mechanical properties of fabrics (a) bending rigidity properties and warp/weft shrinkages (b) tensile properties.

For both fabrics, the bending rigidity is more important in the weft direction than in the warp direction. However, the same material and yarn count per unit length is used in both warp and weft directions. Thus, this difference is related essentially to the higher linear density of the roving (R1 or R2) used in the weft direction in comparison with the yarn (Y) used in the warp direction for both fabrics. The higher linear density involves a higher number of fibres in the cross section and then a higher thread width and thickness resulting in a higher bending rigidity.

By comparing the two fabrics in term of bending rigidity, for the same materiel direction, and considering the shrinkage percentage in the given directions (Figure 4 (a)), it can be concluded that the fabric bending rigidity is linked directly to the yarn shrinkage, which is related to the yarn path inside the fabric structure. The high shrinkage percentage is accompanied with a higher bending rigidity.

The tensile behaviour of the two fabrics is shown on Figure 4(b) through a specific load-strain curve. The load is normalized (cN/yarn/Tex) by considering the number of yarns per cm and their counts (Tex) in both warp and weft directions. It permits to highlight the effect of yarn/roving structure and the effect of the roving treatment, in comparison to the yarn/roving tensile properties characterized before weaving.

The tensile load-strain curves can be divided in two parts: a non-linear part, referred to the fabric structural response which matches with the loss of crimp in the extension direction, followed by a linear part, where yarns become tight and respond directly to the applied load, referred to the yarn response. In warp direction, the shrinkage percentage is higher in F2 fabric than in F1. It results from a more extended non-linear part leading to a higher strain at break at the scale of the fabric. However, on the linear part, the tangent modulus in the warp direction is similar for the two fabrics. For both fabrics, properties are better in warp direction than in weft direction, which can be analysed with regard to the yarn scale (yarns used in warp direction for the two fabrics, are stronger with higher breaking specific load than rovings used in weft direction).

When comparing the fabric specific load in warp direction (Figure 5 (b)) to the yarn behaviour characterized at the yarn scale (Figure 2 (a)), a loss of breaking tenacity is notice. That is attributed to a decrease in twist and to damage caused by the high tension necessary applied on the warp yarn in the warping preparation process weaving processes. In weft direction, the difference in the shrinkage percentage between F1 and F2 is more important resulting in higher elongation due to the loss of the crimp in F2. Similarly, when comparing the fabric specific load in weft direction (Figure 4 (b)) with the roving behaviour characterized at the yarn scale, (Figure 2), higher breaking tenacity is imparted especially for R2. That is related to the impact of the other orthogonal yarns (warp) that compact and compress the roving leading to an increase in the inter-fibre cohesion in the roving structure giving better strength.

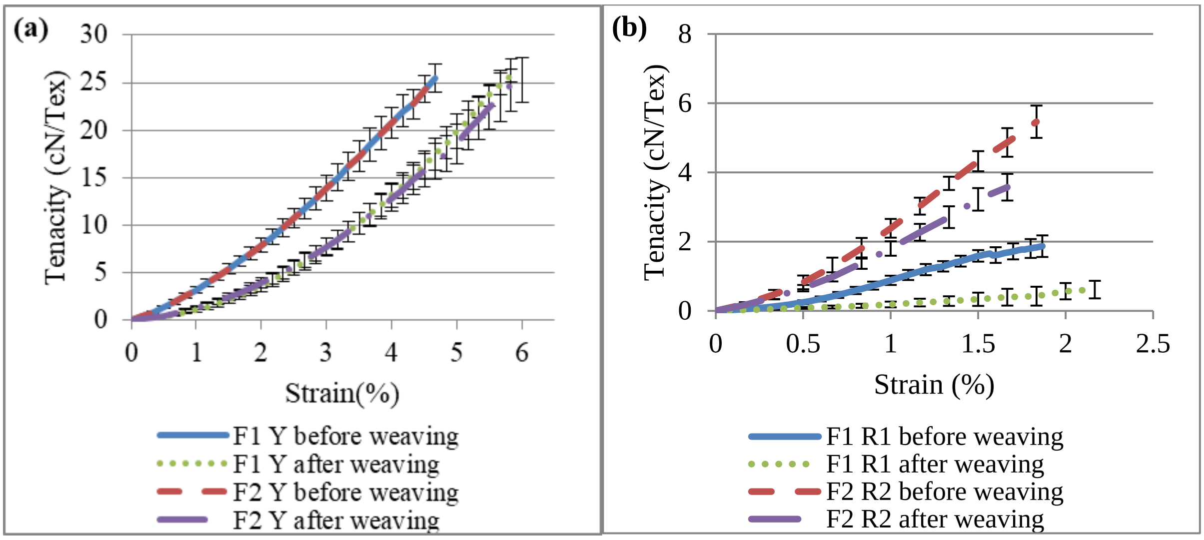

Figure 5. Influence of weaving process on yarns mechanical behaviour (a) warp yarns (b) weft yarns.

The impact of the weaving process on the yarn tensile properties is observable on Figure 5 (a) and Figure 5 (b) giving the tenacity-stain curves for the warp and weft yarns respectively. In this section, the tensile behaviour of a thread extracted from the manufactured fabric is compared to the behaviour of this thread before weaving. For warp yarns, the weaving process leads to an increase of the strain at break of the yarn and a decrease in the curve slopes in the first part. The maximal load for the warp yarn used for F1 and F2 fabrics are equivalent and their apparent rigidity in the linear part is similar. The breaking tenacity for the warp yarn extracted from the fabric is higher than the specific maximum load (cN/Tex) of the fabric in the warp direction. This is attributed to the supplementary loads induced by the micro bending in the crimping areas. The twist level of yarns was also measured on yarns extracted from the fabrics, and the properties are similar to those of yarns from the bobbins before weaving. Indeed, the twist level is not impacted by the weaving process.

For weft, the mechanical properties are affected by the weaving process and a different mechanical behaviour is observed between F1 and F2 fabrics. For F1 fabric, the strain at break is higher after weaving, but the maximal load and the two apparent initial rigidities are lower. In F2 fabric, the strain at break and maximal load in the weft direction also decrease after weaving but the apparent rigidity remains similar.

The weft rovings are more damaged than the warp yarns during weaving process due to the used technique for the weft insertion operation. The weft roving is winded into a small bobbin to be inserted inside a shuttle used to pass the weft thought the warp shed. This process induces a de-twisting of the weft reinforcement and a bending damage in view of winding a thick roving around the small and thin tube of the shuttle. The tenacity at break of the weft yarns extracted from the fabric is lower when compared to the strength of the fabric itself in the weft direction. So, warp yarns may increase the cohesion between the fibres inside the roving due to the applied transverse compression. It leads to a high strength at the scale of the preform.

3.4. *Composite scale*

The tensile properties of the composite samples made up of the two woven fabrics are presented in Table 5. C1 composite is reinforced by F1 fabric and C2 composite by F2 fabric. The obtained tensile properties in weft direction are higher than in warp direction due to higher fibre content in this direction.

This is attributed to the roving linear density which is higher in the weft direction than the one of yarn in warp direction. In the weft direction, the properties are similar for C1 and C2. Thus, it can be concluded that there is no significant impact of the chemical treatment on the composite behaviour.

Table 5. Mechanical properties of composite materials.

		Strength (MPa)	Modulus (GPa)	Strain at failure (%)
FLAX1	Warp direction	91.5 ± 1.0	9.0 ± 0.3	1.71 ± 0.10
(C1)	Weft direction	126.0 ± 6.0	12.0 ± 0.6	3.10 ± 0.10
FLAX2	Warp direction	90.0 ± 5.0	9.3 ± 0.1	1.82 ± 0.09
(C2)	Weft direction	118.0 ± 6.0	12.7 ± 0.3	2.44 ± 0.17

Even if a low tensile resistance was observed at the scales of roving and fabric in roving direction (Figure 2 (a) and Figure 4 (b)), a good tensile behaviour is obtained at the composite scale. Effectively, at the yarn and dry fabric scales, the tensile behaviour is governed by the inter-fibre friction. On the contrary, at the composite scale, the stress between fibres is transferred via the resin and through the fibre/matrix interface.

The tensile properties of the composite materials manufactured in this study were also compared to the tensile properties of other composite materials reinforced by natural fibres, such as flax and jute, listed in the open literature (Table 6), such as in Torres and al. [5] or in Bensadoun's Thesis [6]. These composites were also made up woven fabrics, like C1 and C2 in our study, or are stratification of unidirectional or quasi unidirectional fabrics, for Lineo reinforcement. The Lineo FlaxPly composite, from [5], is a crossply woven textile composite, reinforced by 4 plies of quasi-unidirectional fabric (95% of fibres in main direction and 5% of fibres in transverse direction) and the Lineo FlaxTape composite, from [6], is a crossply laminate, reinforced by 4 plies of unidirectional fabric (nonwoven with fibres totally aligned in the same direction). For these two composites, two plies are laminate in 0° direction and 2 plies in 90°, to obtain reinforcements in the twi main directions of the composite materials, like with woven fabrics. Currently, composites made with Lineo FlaxPly (with a crossply stacking sequence) are widely used for the manufacturing of plant fibres composites in industry. The areal density of F1 (310 g/m²) and F2 (290 g/m²) fabrics is positioned between the ones of the two Lineo reinforcements (180 and 200 g/m²) and Biotex preforms (from 400 to 550 g/m²) and similar to Libeco Flax Plain Weave (285 g/m²) used to manufacture the composites in the cited references. However, the fibre volume fraction is higher for C1 and C2 (about 45%) than the other composites (between 30 to 40%) [5]. C1 and C2 have higher strength and stiffness than the other composites except for the two composite reinforced by Lineo fabrics, where properties can be judged similar. These results are nevertheless promising for the future of the study. The use of FlaxTape reinforcements is currently the reference for natural fibres composites, due to the unidirectional structure: properties are not influenced by some out-of-plane orientations resulting from twisting of yarns or interlacement of warp or weft yarns, as it can occurs with quasi-unidirectional or woven fabrics. Indeed, properties of C1 and C2 composites, made up woven fabrics whose properties are not optimized, are in the same range than the best reinforcement currently available. Woven fabrics are advantageous for composite manufacturing because they are easier to handle and to drape.

Table 6. Comparison with other natural fibres composites materials from literature.

Reinforcement	Areal density (g/m^2)	Number of plies	Fibre volume fraction (%)	Strength (MPa)	Modulus (GPa)	Strain at failure (%)
Lineo FlaxPly [5]	180	4 $[0/90]_2$s	31	147.6 ± 8.3	8.5 ± 0.6	2.15 ± 0.10
Lineo FlaxTape [6]	200	4 $[0/90]_2$s	40	126 ± 7	14.5 ± 0.8	1.08 ± 0.16
Biotex Flax 7-1 Satin weave [5]	400	4	35	102.8 ± 3.2	8.2 ± 0.6	1.70 ± 0.11
Biotex Jute 2-2 Twill Weave [5]	550	4	36	63.1 ± 3.6	6.4 ± 0.6	1.21 ± 0.11
Biotex Jute Plain weave [5]	500	4	40	66.7 ± 3.5	6.4 ± 0.5	1.33 ± 0.11
Libeco Flax Plain Weave [6]	285	4	40	135 ± 18	12.6 ± 0.4	1.69 ± 0.32
Composite Evolution Flax 2-2 Twill [6]	400	6	40	120 ± 2	12.8 ± 0.4	1.65 ± 0.14
Hexcel/Safilin Flax 2-2 Twill [6]	200	4	40	126 ± 9	12.9 ± 1.1	1.52 ± 0.13

4. Conclusion

A multi-stage and multi-scale analysis was conducted to better understand the influence of the plant reinforcement features (including single fibre properties, roving, yarn and preform textile and mechanical properties) on the mechanical behaviour of the final composite.

So, the textile and mechanical properties at each manufacturing stage were determined. A chemical treatment is proposed and carried out on the roving to improve its weavability. It induced an increase in the tensile strength of the roving. An obvious decrease in the breakage and waste during the reinforcement processing is then noticed. It is hypothesized that this treatment increases the inter-fibre cohesion in the roving. Interestingly, this treatment doesn’t affect neither the tensile properties of the fibres themselves nor those of the final composite.

The results obtained at the yarn scale suggest that the yarn/roving behaviour under tension is mainly governed by inter-fibres friction and the twist has an obvious impact to improve the breaking tenacity. Even if the chemical treatment significantly improves the roving tenacity, it cannot lead to the tenacity obtained with twisting and sometimes required for weaving, at least in one of two main material directions. That’s why the roving (R1 and R2) were not used in the warp direction when manufacturing the fabrics.

At the fabric scale, several conclusions can be drawn. The chemical treatment performed on the roving brings more air permeability to the fabric, but has no significant impact on its mechanical behaviour. The fabric bending rigidity is highly influenced by the yarn linear density. A higher rigidity is obtained in the roving direction with higher yarn/roving linear density. During the weaving process, the yarns in warp direction are subjected to a cyclic extension that leads to a slight decrease in the yarn breaking tenacity but an increase in the strain at break. The roving is more affected by the weaving process due to the weft insertion operation using a shuttle. Finally, at the composite scale, quite high tensile stiffness and strength are obtained in both warp and weft directions. So, the results obtained at the scale of the composite using these flax preforms are very promising.

In the upcoming work more parameters will be considered in the multi-scale analysis, such as raw material type, yarn count, treatment type and weave.

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