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Compressive and tensile behaviour of unidirectional composites reinforced by natural fibres: Influence of fibres (flax and jute), matrix and fibre volume fraction

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ABSTRACT

Despite the wide development of biocomposites, their compressive behaviour is still not well understood. In this paper, the longitudinal compressive and tensile behaviour of unidirectional natural fibres is studied through a parametric analysis taking into account the nature of the fibre (flax or jute), the matrix (thermoplastic and thermoset: PP, PP/MAPP, PA11, epoxy or acrylic), the fibre volume fraction and the fibre/matrix bond strength. In parallel with this approach, the quasi-static tensile behaviour is also investigated to allow comparisons. At low strains, the compressive and tensile moduli are closely similar. On the other hand, the compressive strength is systematically lower than the tensile strength whatever the fibre and matrix used. With a PP matrix, use of a coupling agent (MA) to improve the Interfacial Shear Strength (IFSS) leads to an increase of strength, which highlights the importance of this parameter. The compressive strength increases with the fibre volume fraction, but the maximum value remains lower than 140 MPa. Back calculation allows us to estimate the compressive strength of the flax fibres as 240 MPa, which appears as a current limit for the dimensioning of biocomposite structures.

1. Introduction

Plant fibres are being increasingly developed for the reinforcement of composite materials. Among many plant fibres, flax is particularly used for this purpose. The interest in flax cultivation in a European context is explained by the availability of the fibres, the control of all steps (from seeds to fibres) and their good tensile mechanical properties [1].

The tensile behaviour of biocomposite laminates has been widely studied to analyse the potential for reinforcement of flax fibres, but their compressive behaviour is still poorly understood. Indeed, these materials are still in the optimization phase and it is a complex task to carry out compressive tests. In addition, many parameters can influence the performances such as the fibre and resin properties, the interface bond strength, void content, fibre volume fraction and fibre misalignment, as well as the difference in Poisson ratio between fibre and matrix. We also need to consider the viscoelastic behaviour of the matrix, cross-linking of the thermoset resin, non-isotropic properties of the fibres, scattering of the mechanical properties of the reinforcement, presence of damage within the laminate, loading speed, residual thermal stress and the type of compressive test selected [2–10].

Table 1 shows the longitudinal compressive mechanical properties of several unidirectional composites reinforced by flax fibres [11–16]. For the data set (Table 1), the compressive strength remains below 200 MPa and is always lower than the tensile strength. Thus, this mechanical parameter is of potential importance for the development of biocomposites.

This article presents a detailed investigation of the longitudinal compressive behaviour of composites reinforced by unidirectional plant fibre tapes. We study and discuss the influence of the fibre type (flax or jute), polymer (PP, PP/MAPP, PA11, epoxy or acrylic), volume fraction and the quality of interfacial shear strength (IFSS) with a maleic anhydride grafted PP (MAPP).

2. Materials and methods

2.1. Fibres

The flax *(Linum Usitatissimum* L.*)* reinforcement used here is a tape of unidirectional fibres held together without any twist. When using this product (Flax-Tape, manufactured by Lineo® [17]), the fibres are sprayed with a water mist that reactivates their external layer of pectin

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Table 1
Unidirectional composites reinforced by flax fibres. Longitudinal compressive and tensile properties (Literature data).

Matrix	Fibre volume fraction (%)	Compressive modulus (GPa)	Compressive strength (MPa)	Tensile modulus (GPa)	Tensile strength (MPa)	Remarks	References
Phenol formaldehyde	~70	41.4	163	41.4	310	Gordon aerolite® Year 1939	[11]
Phenol formaldehyde	~75	48.3	182	48.3	413.7	Gordon aerolite® Year 1945	[12]
Epoxy	~43	30	119-141			Function of chemical treatment	[13]
Epoxy	43.9	24.7	136	22.8	318		[14]
Epoxy	40	15.1	136.9	23.9	222.9		[15]
Epoxy	50.97	30.32	127.11	31.4	286.7		[16]

cement. This ensures cohesion of the parallel fibres, and allows handling of the layer without misalignment or separation of the fibres. For this study, the areal weight of the Flax Tape is taken as 200 g/m^2.

Gold of Bengal (JUTE lab project) supplied the jute fibres (Tossa variety (*Corchorus olitorius* L.)) coming from Jamalpur District in Bengal, which were cultivated in 2014. Jute stems were retted and stripped to extract fibres, then hackled without being twisted and aligned to produce single UD layer (630 g/m^2). Fibres were held by a weft yarn.

Flax and jute fibres exhibit different mechanical properties due to different biochemical composition, morphology and microstructure [18].

2.2. Polymers

Petroleum-based polypropylene (PP) was chosen as a reference material since it is one of the most extensively studied thermoplastic polymers, particularly in biocomposites. The PP used here is PPC 10642 supplied by Total Petrochemicals, with an MFI of 44 g/10 min at 230 °C. A PP grafted with maleic anhydride (MAPP) was also used as a coupling agent to improve the fibre-matrix adhesion with vegetal fibres [19]. This agent supplied by Arkema (Orevac CA 100) has an MFI of 10 g/10 min at 190 °C, and was added to the matrix at a loading of 4 wt%. The PP matrix mixed with the MAPP coupling agent is referred to below as PP/MAPP.

The polyamide 11 (PA11) used in this study is a bio-based resin supplied by Arkema under the trade name Rilsan®.

A thermoplastic liquid resin (liquid initially at room temperature) (Elium RT 150) manufactured by ARKEMA was also used. This acrylic resin polymerization is triggered by peroxide (CH50x). It can be processed by RTM or LRI as a thermosetting resin, whereas the matrix obtained after polymerisation is thermoplastic. Although this acrylic resin (named Elium®) is claimed to be thermoplastic by the supplier, no independent studies are currently available showing that its recyclability is similar to thermoplastics. After hardening for 24 h at 25 °C, all samples were post-cured following the supplier's recommendations (4 h –80 °C).

An epoxy resin (Axson, Epolam 2020) was used as a matrix, mixed with its aliphatic amine hardener at a ratio of 100:34. After hardening for 24 h at 25 °C, all samples were post-cured following the supplier's recommendations (3 h – 40 °C; 2 h – 60 °C; 2 h – 80 °C; 5 h – 100 °C). Their tensile mechanical properties are shown in Table 2.

Table 2
Tensile mechanical properties of matrices.

Matrix	Young's modulus (GPa)	Maximal Stress (MPa)	Strain at break (%)
PP	1.80 ± 0.02	20.1 ± 0.4	11.5 ± 4.4
PP/MAPP	1.60 ± 0.01	19.2 ± 1.2	11.2 ± 4.1
PA 11	1.14 ± 0.08	45.9 ± 1.8	283.5 ± 28.7
Epoxy	3.30 ± 0.01	78.1 ± 6.2	3.1 ± 0.5
Acrylic	3.10 ± 0.03	52.3 ± 5.6	2.3 ± 0.5

2.3. Composite manufacturing

For composite manufacturing, solid thermoplastic polymers (PP, PP/MAPP and PA11) films were extruded and calandered with a thickness of 140 µm to carry out film stacking with flax and jute reinforcement. Film processing was carried out using a Brabender Plasticorder twin-screw extruder (model W 50 EHT) equipped with a cast die; the width and the thickness of the die are 150 mm and 1 mm, respectively. Temperatures of the crew from alimentation to die for PP and PA11 films are 200/190/190/190 °C and 220/210/210/200 °C, respectively. Temperature of rolls was 45 °C and rotation speed of the screw and of the rolls were 20 rpm and 12 rpm, respectively.

Unidirectional composites were manufactured by film stacking using a Labtech©50T moulding press with a 30 × 30 cm^2 heating plate. Flax or jute preforms and polymer films were stacked alternatively. This assembly was placed between two aluminium cover plates, which were then inserted into the moulding press. The press was preheated to 210 °C and the composite assembly was maintained for 2 min at this temperature; then, a pressure of 20 bars was applied during 3 successive 1-min steps at intervals of 5 bars and a final step held for 3 min at 20 bars. Thus, the duration of the total hot cycle at 210 °C was 8 min. After the dwell time, the assembly was cooled down to 30 °C in 3 min. The fibre volume fraction varied from 20 to 60%.

In the case of composites made with thermoset resin (epoxy) or liquid thermoplastic resin (acrylic), flax or jute unidirectional laminates were impregnated manually and then in a press to eliminate voids (Labtech © 50T moulding press) and check the fibre volume fraction. When closing the press, the distance between the plates is defined with shims to control the fibre volume fraction. After hardening, post curing of composites was carried out to allow cross-linking of the epoxy resin or polymerisation of the acrylic resin. The thermal cycle follows the manufacturer's technical data sheet.

Unlike glass fibres, vegetal fibres are discontinuous. Thus, during the impregnation phase, the orientation of the fibres cannot be controlled by applying a tensile force.

The observation of sample cross-sections with SEM allows us to check the low occurance of porosity and assess the fibre volume fraction. Fig. 1 shows some examples of flax-PP/AMPP and jute-PP/AMPP composite cross-sections.

2.4. Samples thickness

The sample thickness has an influence on the compressive strength of the laminate. For an unidirectional composite reinforced by glass or carbon fibres, and with the selected compression equipment (ITRII), the minimum thickness of the sample is 2 mm [3]. If the thickness is too small, the measured value will not be representative. If the thickness is excessive, there is an increased risk of defects (porosities, misalignment of fibres, highly heterogeneous microstructure, etc.). Thus, preliminary

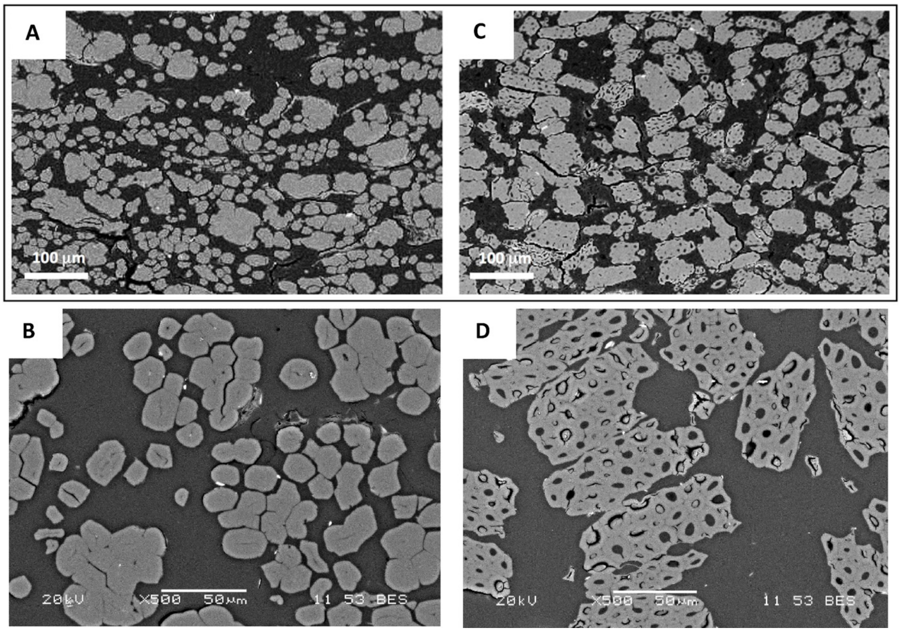

Fig. 1. SEM cross-sections of flax-PP/AMPP (A–B) and jute-PP/AMPP (C–D) UD composites (fibre volume fraction = 60%).

tests were carried out on PP/flax with a fibre volume fraction of 50% to define the thickness of the samples for the characterisation conditions. For this test, two gauges were bonded (one on each face) to monitor the compressive behaviour (during the test, the two gauge readings are compared). The thickness is set at 2.5 mm, since this corresponds to the maximum strength. At greater thickness, the decrease in strength is attributed to the defects and the non-homogeneous distribution of fibres inside of the ply.

2.5. Mechanical properties of biocomposites

Tensile tests were carried out using an Instron 5566 A instrument in a laboratory with controlled temperature and relative humidity (23 ± 0.5 °C, 48 ± 2% RH). The standard selected is ISO 527 and the useful length of the samples is 136 mm and the width 25 mm (ISO 527-4). For the tensile tests, a 10 kN sensor, an axial extensometer was used with a nominal length of 25 mm and a loading rate of 2 mm min^{-1}. The tensile modulus, strength and strain at break are calculated from an average of at least 7 samples.

The compressive tests were carried out with the same instrument and environment. The standard selected is ISO 14126 and the reference test ITRII. Fibre glass tabs (± 45° /thickness = 0.8 mm) were bonded at the end of the sample with an epoxy adhesive to reduce the risk of breakage in the jaws. The useful length of the samples is 10 mm and the width 10 mm. Each face of each sample is equipped with a strain gauge (KYOWA KFG-2-120-C1-11, length = 2 mm), in order to compare the strains and avoid bending behaviour. The loading rate was 1 mm/min. The compressive modulus is determined for strains between 0.05% and 0.1%. The average compressive modulus and strength at break is calculated from an average of at least 7 samples.

It is also worthy to note that different testing speeds were used for determination of tensile and compression properties of composites (2 and 1 mm/min, respectively – Speeds given by the standards). It is known that mechanical behaviour of polymer composites strongly depends on the loading rate. Despite difference in the testing speeds used in this work for tensile and compression tests is not very critical. Moreover, it would be logical to take into account the free length of the specimens (strain speed).

2.6. SEM observations

Composite samples were embedded in an epoxy resin before polishing. They were then metallised with gold before being observed under a JEOL JSM 6460LV scanning electron microscope.

3. Results: multiparametric analysis

3.1. Rupture mechanism in compression of composites reinforced with flax and jute

Typical kinking failure is presented in Fig. 2 on example of flax-PP/MAPP (Vf = 50%) and Jute-PP/MAPP composites. As currently observed in composite materials compressive damage and rupture correspond to fibre microbuckling. Jute composites exhibit a heterogenous microstructure (Fig. 2B) which is explained by areal weight of the preform used (630 g/m^2 for jute against 200 g/m^2 for flax) but also by

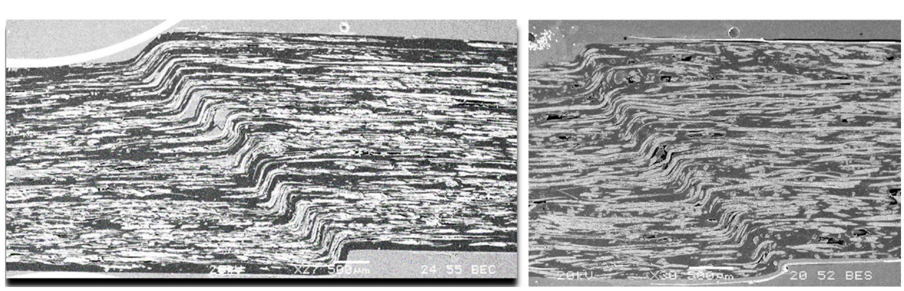

Fig. 2. Images of typical kinking failure in flax-PP/MAPP (A) and Jute/-PP/MAPP (V_f = 50%) composite in longitudinal compression.

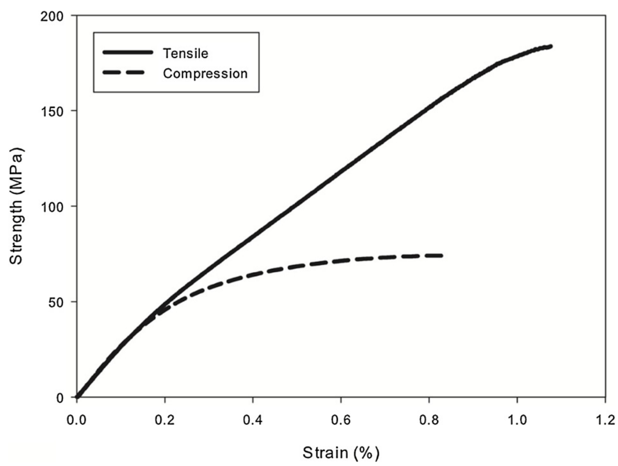

Fig. 3. Compressive and tensile longitudinal behaviour of flax-PP composites (Vf = 50%).

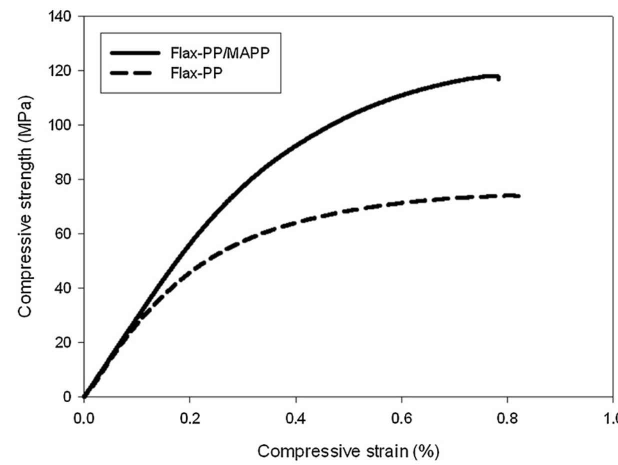

Fig. 4. Compressive behaviour of flax-PP and flax-PP/MAPP (VF = 50%).

the lower fibre bundle individualization.

3.2. Comparison of the compressive and tensile behaviours of a flax/PP laminate

Fig. 3 shows a comparison between the compressive and tensile behaviours of a PP/flax (Vf = 50%). The tensile and compressive tests lead to different strain-stress curves because compressive loads involve a more pronounced non-linear behaviour. However, for small strains, the slopes of the curves are similar and therefore the compressive modulus is equal to the tensile modulus ($E_{tensile}$ = 30.8 ± 3.2 GPa vs $E_{compression}$ = 29.9 ± 1.0 GPa (Fig. 3)).

The tensile behaviour is close to that usually observed in composites [20,21], i.e. non-linear mainly due to plant-fibre microstructure. A flax fibre can be considered as equivalent to a stack of plies reinforced by cellulose fibrils arranged in a helix and oriented at an angle of about 10° [22]. During a tensile test, the fibre behaviour depends on the constituents, but is also influenced by two mechanisms [23,24]: partial reorientation towards the axis of stress of the fibrils and sliding of the latter with respect to one another.

During tensile loading, it is possible to observe damage development (fibre breakage and sliding, etc.) occurring just before the sample break. In compression, the marked non-linear behaviour is explained by the microbuckling of fibres as shown in Fig. 2. We note that this kind of failure mechanism is observed for all the materials studied in the present study.

Analysis of the stress-strain data highlights that the tensile stress are always higher than the compressive stress ($\sigma_{tensile}$ = 193 ± 15 MPa vs $\sigma_{compressive}$ = 74.9 ± 3.8 MPa (Fig. 2)). Although the compressive behaviour of unidirectional with a PP matrix is not described in the literature as far as we know, these observations confirm the results of several previous studies (Table 1) [11,12,14–16].

It is interesting to compare our results on vegetal fibre composites with composites reinforced with synthetic fibres, using some examples available in the literature [25,26]. For a carbon (high strength)/epoxy composite, the longitudinal compressive strength is close the longitudinal tensile strength, but this is not the same with aramid fibres. With polymeric fibres, the compressive strength of a unidirectional composite is clearly lower than the tensile stength, and the compressive failure of a Kevlar/epoxy composite is caused by kink band failure [27], induced by the specific pleated sheet structure of aramid fibres [28]. Many illustrations of fibre microbuckling are given in the literature, such as for aramid (Kevlar), HT-PBZT, HT-PBO [27], PE, NTP, PBT, ABPO [29] and UHMWPE [30].

3.3. Influence of the quality of fibre/matrix interface bond strength

The compression non-linear behaviour of a unidirectional composite is hardly modified by MAPP grafting (Fig. 4). Although the initial modulus is not influenced at low strains, the compressive and tensile strengths increase greatly (+47% and +21%, respectively (see Table 3)) with addition of PP/MAPP. Indeed, for a PP Matrix, use of a coupling agent (MAPP here) allows us to increase the interfacial shear strength with flax fibres [31].

3.4. Influence of the matrix

Table 3 presents a comparison between different thermoplastic resins (PP, MAPP and PA11), thermoset (Epoxy) and "liquid thermoplastic" (fibre volume fraction near to 50%). Whatever the nature of the polymer matrix, there is only a slight difference between tensile and compressive moduli. This highlights the preponderant contribution of fibre stiffness in this loading direction.

Using PP, PP/MAPP or PA11, acrylic or epoxy matrix leads to a variation of compressive as well as tensile strength. Compressive strength is always significantly lower than tensile strength. Unidirectional flax/epoxy shows a much higher tensile strength. Compressive strength is a function of the fibre/matrix bonding as mentioned in the previous section. IFSS (Interfacial Shear Stress) between flax fibre and the tested matrices has been studied for PA11 [33], PP and MAPP [31], epoxy [34], and transverse strength for acrylic [32]. Globally, the lower interfacial strength observed for PP and acrylic resin (to a lesser extent) logically leads to a lowering of compressive strength.

3.5. Influence of fibre volume content

Tensile and compressive moduli show a similar quasi-linear trend with increasing fibre content (Fig. 5a), thus emphasizing the role of flax fibres as a reinforcement. The modulus, calculated at the beginning of the stress-strain curve, is mainly dependent on the fibre stiffness. At a low strain level, the modulus is not influenced by the micro-bulking of fibres that occurs in compression mode. In addition, using a thermoplastic or thermoset matrix leads to similar results, Fig. 5b shows that, whatever the polymer matrix, its influence on composite stiffness is negligible, despite significant stiffness differences between the two polymers. The composite stiffness is controlled by the fibre stiffness and volume fraction.

The increase in compressive strength is limited (Fig. 6) compared to the raw matrix whatever the nature of the matrix. With an epoxy matrix, the compressive strength is linearly proportional to the fibre volume fraction. Results are more scattered with PA11. This dispersion is

Table 3
Mechanical properties of unidirectional composites for several polymers (fibre volume fraction of 50%).

	Fibre volume fraction [%]	Compressive modulus (GPa)	Compressive strength (MPa)	Tensile modulus (GPa)	Tensile strength (MPa)
Flax-PP	49.2	29.9 ± 1.0	74.9 ± 3.8	30.8 ± 3.2	193.0 ± 15.0
Flax-PP/MAPP	49.8	28.9 ± 3.1	110.1 ± 18.4	31.0 ± 1.8	234.0 ± 23.0
Flax-PA11	50.1	29.3 ± 1.4	133.9 ± 8.5	30.0 ± 2.3	257.9 ± 12.3
Flax-Acrylic	48	27.9 ± 2.1	101.3 ± 5.3	27.6 ± 1.6	243.8 ± 12.4
Flax-Epoxy	50.9	25.2 ± 1.9	115.4 ± 5.9	26.0 ± 2.0	408.0 ± 36.0

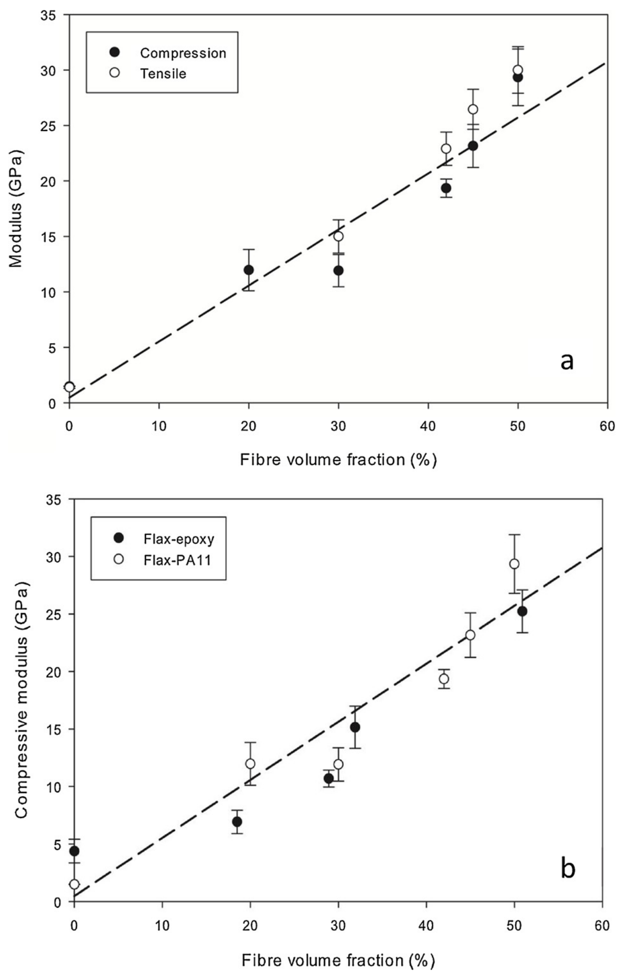

Fig. 5. (a) Compressive and tensile modulus as a function of fibre volume fraction. Unidirectional flax-PA11. (b) Compressive modulus as a function of fibre volume fraction. Unidirectional flax-epoxy and flax-PA11.

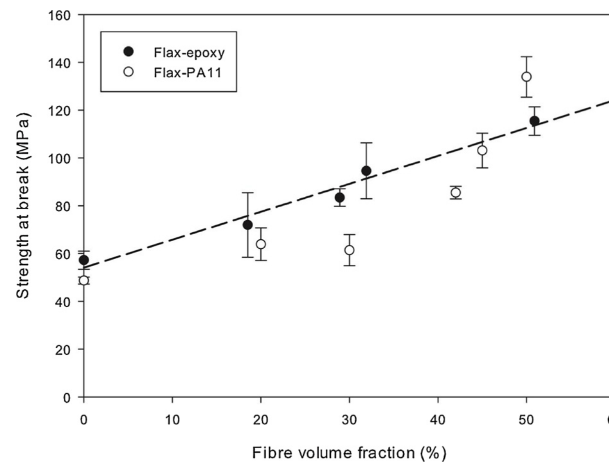

Fig. 6. Compressive strength as a function of fibre volume fraction. Flax-epoxy and Flax-PA11 composites.

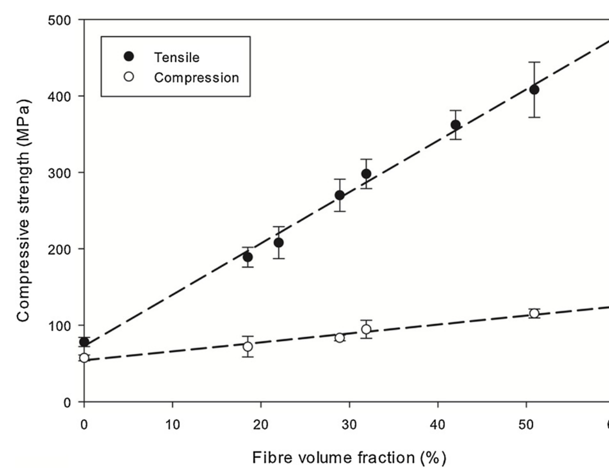

Fig. 7. Flax-Epoxy. Comparison between tensile and compressive strength as a function of fibre volume fraction.

due to a less homogeneous distribution of fibres in the composite [20], mainly for low fibre volume fractions. The technique of film stacking used here leads to the creation of an interlaminar zone rich in matrix in this case. In addition, the PA11 exhibits a more viscous behaviour than epoxy (it is a limiting factor for fibre impregnation) and a lower stiffness (Table 2).

Fig. 7 shows the difference between the tensile and the compressive strength for an epoxy matrix and as a function to the fibre volume fraction. The increase is almost linear for the two loadings and the compressive strength remains clearly lower than tensile strength. These observations illustrate that, whatever the fibre ratio and the matrix used, the compressive stresses are lower than those observed in tension, thus confirming the behaviours shown in Fig. 2. The micro buckling mechanisms observed (Fig. 3) become more disadvantageous as the fibre ratio increases, since the difference in stress between the two stressing modes increases very significantly with the fibre volume fraction; the tensile strength is +162% and +253% for fibre volume fractions of 18.5% and 50.9%, respectively, relative to the compressive strength.

3.6. Influence of fibre nature: flax and jute

Although porosity content is similar (vp ≈ 1.5%), flax and jute fibres exhibit different mechanical properties. Table 4 summarizes the influence of fibre nature on the laminate (PP/MAPP matrix and Vf = 60%) compression modulus and strength. Thus, composites reinforced by jute fibres have less favourable compressive properties than flax counterparts (Table 4). Despite a fibre volume fraction of 60%, the compressive strength of jute-PP/MAPP is lower than 100 MPa. Indeed, jute fibre possess lower tensile properties than flax, while their length (elementary fibre scale) is smaller (between 0.8 and 7 mm for jute and between 13 and 60 mm for flax) [35]. In addition, the composite

Table 4
Unidirectional flax-PP/MAPP and jute-PP/MAPP. Influence of fibre nature on mechanical properties (fibre volume fraction of 60%).

	Flax		Jute	
	Compression	Tensile	Compression	Tensile
Modulus (GPa)	30.9 ± 1.3	34.4 ± 2.6	19.8 ± 1.4	23.1 ± 2.4
Strength (MPa)	127.7 ± 3.4	204 ± 23.0	94 ± 5.4	145 ± 10.0

microstructure of jute fibre is mainly composed of fibre bundles, unlike flax fibre laminates (Fig. 1), due to less efficient fibre extraction as well as the higher lignin content of jute, inducing more cohesive fibre bundles.

4. Discussion

As shown in the previous section, the compressive properties of plant fibre biocomposites may be considered satisfactory because the values are very close to the tensile moduli (for low strain). However, the compressive strength of such composites is only moderate, so we need to investigate further to provide an explanation.

To allow comparisons with jute and wood fibres, back calculation allows us to estimate an apparent fibre compressive strength ($\sigma_{fL\ C}$) from the compressive strength of the unidirectional composite ($\sigma_{UD\ L\ C}$) using the following relationship [27]:

$$\sigma_{fL\,C} = \frac{\sigma_{UD\,L\,C}}{Vf} \tag{1}$$

The main hypothesis is that the compressive strength is linearly proportional to the fibre volume fraction (Vf). This hypothesis has been checked for glass fibres [36]. Using the set of results from the present study, the longitudinal compressive strength of flax and jute can be estimated at around 240 and 155 MPa, respectively. It is well known that fibres with poor compression properties give composite laminates which are also weak in compression, the typical example being Kevlar© reinforced polymers [5].

However, back calculation should taken with caution. Indeed, fibre/matrix quality is not taken into account while it influences the compressive strength. This is illustrated in Table 3 with Flax-PP/MAPP and flax-PP comparison. Without coupling agent, compressive strength of flax is estimated to be around 152 MPa against 240 MPa when calculation is made with PP-MAPP.

The compressive strength of an elementary fibre can be measured or indirectly estimated. For example, the methods employed for determining the compressive strength of single fibres include the loop test, the bending beam test, as well as tests using fibres encapsulated in a polymer block, broken fibre fragment length, tensile recoil or direct compression [27]. Moreover, a number of difficulties are encountered in compression testing of single fibres. First, the handling of fibres is very complex because of their small dimensions and the reproducibility of the measurements must be checked. In addition, it is often difficult to accuratly pinpoint the initiation of compression failure (flax fibres do not show a brittle behaviour due to their microstructure). Finally, in many tests, compressive strain is measured rather than compressive strength, and compressive strength is calculated using the fibre tensile modulus. This may result in overestimation since the compressive modulus may be lower than the fibre tensile modulus while the fibre compressive stress-strain curve is nonlinear [27].

Bos et al. [38] estimated the compressive strength of flax fibres using a loop test [37]. For the selected batch, the stress at break is 1200 MPa in compression and 1522–1834 MPa in tensile loading mode. Despite the experimental difficulties and the small number of samples (9), as well as the assumptions and limits of the method [27], the results obtained by the loop test provide an indication of compressive strength which has not yet been corroborated by other studies.

Wood is a composite material composed of an assembly of fibres mainly oriented along the axis of primary growth. During loading along the grain (tensile and compressive load), the wood behaviour [39] is similar to that of an unidirectional flax composite laminate (Fig. 2). In addition, the compressive strength of wood are roughly one-third of the tensile strength [39]. The mechanism leading to the compressive break of wood is a kink banding phenomena, such as observed in unidirectional composites reinforced by flax (Fig. 3) and materials reinforced by synthetic fibres [40–42]. The design of wood structures, such as columns and beams, requires a knowledge of fibre compressive behaviour. However, the compressive behaviour of wood is linearly proportional to the specific gravity [41,43,44]. This relationship allows the modelling of structures, and remains valid whether the wood is green or air dried. Thus, Gibson [45] estimated the axial compressive strength of a wood cell wall as 120 MPa, which corresponds to a densified wood with no lumen. This result is of the same order of magnitude as values measured on unidirectional reinforced by flax fibres (see Tables 3 and 4).

Many models are available to predict the compressive strength of a composite material [46,47,8,7]. For example, Argon [46] pointed out that the initial fibre misalignment, ϕ, and the longitudinal shear strength yield, τ_y, are important parameters influencing the compressive laminate strength. Then, Budiansky [47] assumed an elastic-ideally plastic constitutive law and expressed the compressive strength as follows:

$$\sigma_{UD\,L\,C} = \frac{\tau_y}{\varnothing + \gamma_y} = \frac{G_{LT\,UD}}{1 + \frac{\varnothing}{\gamma_y}} \tag{2}$$

where $G_{LT\ UD}$ is the axial shear modulus of the composite and $\gamma_y = \tau_y/G_{LT\ UD}$ is the yield strain in longitudinal strain. This simple equation is chosen here to analyse behaviour, not to predict compressive strength. In typical carbon fibre composites, the fibre misalignments are assumed to be small, between 1° and 5°, and the peak stress relative to the longitudinal shear modulus is high [48]. Eq. (2) could also be used to estimate the longitudinal compressive strength of woods where the fibre misalignment angle (ϕ = fibre misalignment around ray cells) is measured in the range between 7–15° by SEM observation [42,41]. This value enables the prediction of the stress threshold for kink-band formation.

In a previous study [49], we investigated the shear behaviour of unidirectional flax/epoxy as a function of fibre volume fraction, showing the low shear modulus of flax fibres ($G_{f\ LT} \approx$ 2500 MPa), and therefore the low shear modulus of flax fibres reinforced composites (lower than 2000 MPa). Our study also showed the low failure strain ($\gamma_y \sim$ 2%) of flax composite materials.

Therefore, even if flax fibre misalignment is currently a complex parameter to properly estimate, the low longitudinal compressive strength of a unidirectional flax/epoxy could be easily explained by its limited shear stiffness.

5. Conclusion

The present study aims to improve our understanding of longitudinal compressive behaviour of an unidirectional composite reinforced by flax fibres. The strategy used here makes use of a parametric analysis based on an evaluation of IFSS, fibre content and matrix or fibre nature. The results obtained for composites reinforced by unidirectional flax fibres show that, for small strains, the compressive modulus is closely similar to the tensile modulus. However, the compressive strength is always lower than the tensile strength. In compression, the failure mechanism involves the microbuckling of flax fibres (as seen in composites reinforced by carbon, glass or organic fibres).

The enhancement of IFSS using PP/MAPP or by selecting an appropriate matrix leads to better compressive properties. Nevertheless, a large change of polymer matrix or an increase in the fibre volume fraction does not imply a drastic increase of compressive strength, which remains lower than 140 MPa, a value which is competitive with wood. The fibre nature, performance and bundle division (flax or jute) also play an important role.

A simple micromechanical analysis shows that the apparent compressive strength of flax and jute fibre is around 240 and 155 MPa, respectively

Finally, the compressive strength of unidirectional composites reinforced by flax fibres is a limiting property for the modelling of structures. In a similar way with the design of wood structures such as columns and beams, we require a deeper knowledge of plant fibre mechanical behaviour for the production of high-perfomance structures.

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