



FLAX-LINEN & HEMP
TEX AND TECH

Process guide as an entry gate to European Flax-Linen & Hemp composites manufacturing

By the enlarged European Scientific Council
of Alliance for European Flax-Linen & Hemp
March 2026



Alliance for European
Flax-Linen & Hemp

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Part I: Processing windows

A document elaborated by
Alliance for European Flax-Linen & Hemp

With the support of
**The enlarged European Scientific Council
of Alliance for European Flax-Linen & Hemp**

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The Alliance for European Flax-Linen & Hemp & its European Scientific Council

The Alliance for European Flax-Linen & Hemp is the only European agro-industrial organisation that brings together all stakeholders of the Flax and Hemp value chain.

The Alliance for European Flax-Linen & Hemp creates an environment that fosters competitiveness of industrial businesses as part of its three-fold mission of informing members industrials and consumers, supporting the European ecosystem and European expertise, and promoting European Flax-Linen and Hemp as the preferred sustainable and high performance fibres worldwide.

Since 2009, its European Scientific Council unites internationally recognised experts from complementary disciplines, linking fundamental research and applied industrial development within an open-innovation framework. Through coordination of research, harmonisation of methods, knowledge dissemination and technical networking, the Council contributes to structuring and strengthening the European Flax-Hemp innovation ecosystem.

This document has been developed within that collective framework. Its purpose is to facilitate the integration of Flax and Hemp fibre composites into industrial applications by providing a clear, structured overview of processing stages, technical sensitivities, and known boundaries.

It is not an exhaustive scientific review, nor a comprehensive engineering manual including detailed design rules, certification pathways or advanced modelling tools. Instead, **it consolidates current knowledge into an operational reference intended to support informed industrial decision-making.**

Thus, it aims to provide users with support in understanding the fundamental steps involved in the implementation of bio-based composites, taking into account the intrinsic characteristics of plant fibres.

Composite manufacturing involves coupled thermo-mechanical, hydro-hygro and physico-chemical phenomena. With plant fibres such as Flax and Hemp, these multiphysical interactions are particularly influential and require careful control of material-process relationships, due to the specific sensitivity of the reinforcements. Industrial implementation therefore demands specific technical expertise.

Today, the European Flax-Linen and Hemp sector is organised and sufficiently mature to support robust industrial developments. From agricultural production to fibre preparation, textile engineering and composite processing support, the necessary competencies exist within the Alliance and its partners to accompany projects at every stage.

This guide forms part of a broader evolving toolbox that includes technical videos, calculation guidelines, training actions and process-specific methodologies, aimed at fostering knowledge sharing and enabling sustainable industrial growth.

European Scientific Council composition - 2026



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Introduction

Why this document?

The aim of this document is to help composite manufacturers or laboratories **that are not yet familiar with European Flax-Linen and Hemp fibres to successfully take their first steps with these materials.**

While experienced manufacturers may already be familiar with these fibres, we believe that a review of the fundamentals can help prevent common errors and challenge persistent misconceptions about the technical viability of European Flax-Linen and Hemp.

Many projects—both academic and industrial—are addressing advanced topics such as modelling and the interaction of multiple parameters. We look forward to seeing these results disseminated more widely in the coming years!

Developed through the collective and collaborative efforts of the European Scientific Council of the Alliance for European Flax-Linen & Hemp, the members of the Technical Section Uses and partners, this guide is intended to support the integration of Flax-Linen and Hemp fibres into the composites industry.

Flax and Hemp fibres are not intended to replace glass or carbon fibres, but to complement them in application fields where their intrinsic properties offer specific advantages. We would like to contribute to the integration of natural fibre-reinforced composites with other bio-based materials, utilising their properties in a complementary way for a variety of applications. Several industrial-scale material and processing solutions have been developed to take advantage of these properties.

1.1. Why use European Flax & Hemp Fibres?

In the context of increasing demand for environmentally friendly materials driven by growing global environmental awareness, European Flax-Linen and Hemp fibres represent both environmentally and technically relevant solutions.

Compared to conventional industrially produced reinforcements, their production is associated with lower cumulative energy demand and reduced greenhouse gas emissions. **Life cycle inventory data for Flax fibres are available in the Ecoinvent database, and a dedicated assessment tool addressing the processes specific to Flax-Linen is being developed by the Alliance in collaboration with its partner Glimpact.**

Some of their key technical advantages are highlighted below, including their high-specific tensile modulus and strength (see Table 1) and their very good vibration damping¹. Moreover, they have high potential to reduce the environmental impact of composites. This is mainly linked to the fibre volume fraction and mechanical performance obtained from the combination of a process, a reinforcement and a matrix.



1.2. Questions and Preconceptions about Flax & Hemp Fibres

Some of the most common questions and preconceptions when using European Flax and Hemp fibres are:

- **“The natural variability of Flax-Linen and Hemp fibres makes them impossible to integrate into technical applications at an industrial scale”**

The expertise in plant fibre cultivation, processing and blending, combined with mastery of each production step, ensures consistent mechanical properties in the composite reinforcement. Therefore, the synergy of know-how (natural fibre producers, fabric producers, and composite manufacturers) is key to a project’s success.

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Sala, P., et al., 2022. Variability in the elastic and time-delayed properties of structural Hemp fibre composites. Composites Part A: Applied Science and Manufacturing 161, 107116. <https://doi.org/10.1016/j.compositesa.2022.107116>

- **“The moisture sensitivity of Flax-Linen fabrics makes them impossible to manage”**

Flax and Hemp can retain 8% moisture under standard ambient conditions. This moisture content should be considered during composite manufacturing. Please refer to [section 2.2](#) for more detailed explanations.

- **“The lower fibre volume fraction of bio-based composites makes them impossible to use as industrially viable composites”**

The achievable fibre volume fraction depends mainly on the manufacturing process. Whether using BMC/SMC, vacuum infusion or hand lay-up, it is essential to work with your reinforcement supplier to optimise the process and reach the desired fibre content.

The density of natural fibres is influenced by their internal structure: fibres with a large lumen contain more empty space and are less dense, while fibres with thicker walls or a collapsed lumen are denser. Processing can also modify this structure.

The density of Flax and Hemp preforms depends on how they are prepared, and denser preforms are becoming available.

Because of these variations, the true fibre and preform density must be measured rather than assumed in order to obtain reliable fibre volume fraction calculations.

KEY SCIENTIFIC REFERENCES

Le Gall, M., Davies, P., Martin, N., Baley, C. [2018]. Recommended Flax fibre density values for composite property predictions. Industrial Crops & Products. <https://doi.org/10.1016/j.indcrop.2018.01.065>

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Truong, M., Zhong, W., Boyko, S., & Alcock, M. [2009]. A comparative study on natural fibre density measurement. The Journal of the Textile Institute. <https://doi.org/10.1080/00405000801997595>

- **“Natural fibre composites have no ecological interest, as they are perceived to require more resin by mass than glass- or carbon-fibre-based composites.”**

Natural-fibre composites sometimes reach lower fibre volume fractions, which can influence the overall resin content.

Still, there are many effective ways to improve their environmental performance, such as increasing fibre volume fraction through suitable processes, using advanced technical fabrics, or choosing resins with a lower environmental impact. As a result, natural-fibre composites offer a real and promising potential for reducing the environmental footprint of composite materials. Thus, the potential to reduce the environmental impact of composites is real.

- **“Natural fibre composites are not suitable for outdoor or marine applications.”**

Natural fibres absorb moisture, and the resulting swelling may affect the composite’s microstructure. Proper edge sealing prevents this internal damage and ensures long service life. For more demanding environments, such as marine applications, a topcoat is recommended. With these precautions, natural-fibre composites perform well outdoors and in marine conditions, and even if defects occur, they generally remain functional long enough to be repaired.

If the resin system and its processing allow it, it is also possible to prepare natural fibre composites with non-dried, pre-swollen fibres. This greatly reduces further swelling in use and can help mitigate the above-mentioned problems.

Long-lasting products already in use, such as cars or various boats, clearly demonstrate that natural fibres can deliver durable performance in outdoor and marine applications over many years. For example, Alliance’s members, such as BComp, Terre de Lin Technique, Ecotechnilin or Greenboats-Depestele (see [list of our members page 23](#)), have participated in the construction of boat parts or full hulls.



Figure 1: Greenboat Flax composite hull – example of structural natural fibre application. © Greenboat

KEY SCIENTIFIC REFERENCES

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- **“There is poor adhesion between natural fibres and the matrix.”**

In many cases—particularly when both fibre and matrix are polar (e.g., Flax in PLA)—natural adhesion is sufficient and chemical treatments are not required.

For other fibre–matrix combinations, treatments may be used to improve interfacial bonding, as the polar surface chemistry of natural fibres can limit compatibility with non-polar matrices.

Such modifications should be selected based on composite-specific requirements rather than applied systematically.

KEY SCIENTIFIC REFERENCES

Fuentes C., 2014. Interfacial Adhesion in Natural and Synthetic Fibre Composites: a Physical-Chemical-Mechanical Approach, PhD thesis KU Leuven, Belgium. <https://doi.org/10.13140/RG.2.2.36823.52647>

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1. European Scientific Council of the Alliance for European Flax-Linen & Hemp, Vibration damping: the benefits of Flax and Hemp fibre composites, 2023. <https://allianceflaxlinenhemp.eu/en/european-flax-linen-hemp-media-library/3/vibration-damping-the-benefits-of-flax-and-hemp-fibre-composites>

- “The applications are limited to semi-structural components.”

Although many current applications are found in furniture, building materials and automotive parts, Flax and Hemp fibres also have strong potential for structural composites. Their high stiffness and strength result from the alignment of cellulose microfibrils along the fibre axis and their high crystalline cellulose content. Technical reinforcements have been developed to enable high fibre content to be achieved under moderate compaction forces.

Several structural examples, such as bridges or full boat hulls, show that natural fibres can be suitable for load-bearing applications. Reaching this level of performance requires dedicated technical expertise, including advanced numerical modelling. These capabilities are offered by some of our members and several pioneering university laboratories; see our directory and the ESC list at the end of this document.

- “Flax and Hemp fibres are often considered unsuitable for hybrid composite designs.”

Combining different fibres within a matrix produces hybrid composites whose behaviour can be tailored by selecting and arranging fibres with complementary properties. For example, carbon-Flax hybrids can approach the bending stiffness of pure carbon composites while providing significantly higher vibration damping. This effect is mainly observed in bending, with carbon in the outer layers; in pure tension, the response generally follows the rule of mixtures, and stiffness remains lower than that of full carbon laminates. Recent industrial applications such as ski, tennis or paddle raquets are good examples of hybrid composite designs.

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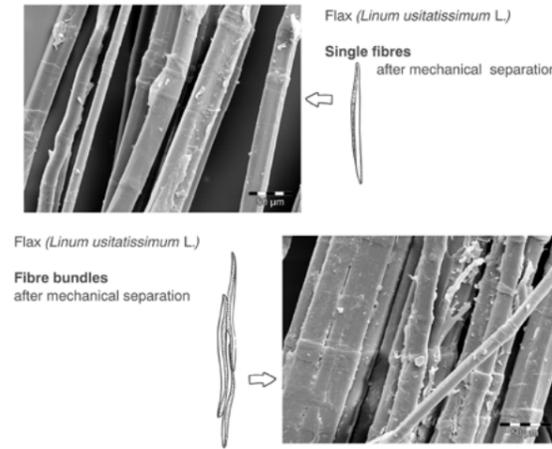


Figure 3: Scanning electron micrographs of single Flax (*Linum usitatissimum* L.) fibres (upper image) and Flax fibre bundles with different thicknesses and a single fibre in front (lower image) (Müssig & Hughes, 2012).

For natural fibres, a range of values is found in literature for their basic mechanical properties, such as Young’s modulus («stiffness») and strength. The influence of plant genetic variety, agricultural growth conditions, and processing conditions (such as extraction method) can all play a role. On top of this, measurement methodology also plays a (too big) role: if properties are measured on single fibres, the spread in properties is emphasised, and proper strain measurement is a big challenge. Also, extraction-induced defects are over-emphasised. Therefore, the Alliance has been advocating to measure fibre properties from Impregnated Fibre Bundle testing² with the use of proper extensometry, as is also common for glass and carbon fibres (ASTM D2343 - Standard Test Method for Tensile Properties of Glass Fiber Strands, Yarns and Rovings used in Reinforced Plastics).

FIBRE	FLAX	HEMP	E-GLASS	S-GLASS	CARBON
Density / g / cm ³	1.4-1.5	1.4-1.65	2.54-2.6	2.48	1,76 (SM), 1,76-1,8 (IM)
Young's modulus / GPa	50-70	30-60	72	86-91	200-300 (SM), 280-350 (IM)
Specific Young's modulus / GPa / g.cm ⁻³	36-50	20-40	30		110-500
Strength / MPa	800-1200	500-700	2000		2500-5000 (SM), 3500-5000(IM)
Specific Tensile Strength / MPa / g.cm ⁻³	400-1100	400	500-1000		1400-3000
Elongation at break / %	1.6-2.0	1.3-4.7	4.7-4.8	5.4-5.7	1,8-2,0

Table 1: Fibres table properties

1.3. Specificities of Flax and Hemp Fibres and Reinforcements

1.3.1. Fibre description

Flax and Hemp fibres can occur either as single fibres (elementary cells with a lumen) or as bundles of single fibres. Their morphology is therefore as important to processing as their physico-chemical properties. Natural fibre reinforcements exhibit a hierarchical structure. Flax may either be processed directly into nonwovens or first assembled into yarns, which are subsequently converted into textile reinforcements. These textile structures can provide either random fibre orientations (e.g., nonwovens) or controlled fibre alignments (e.g., unidirectional fabrics).

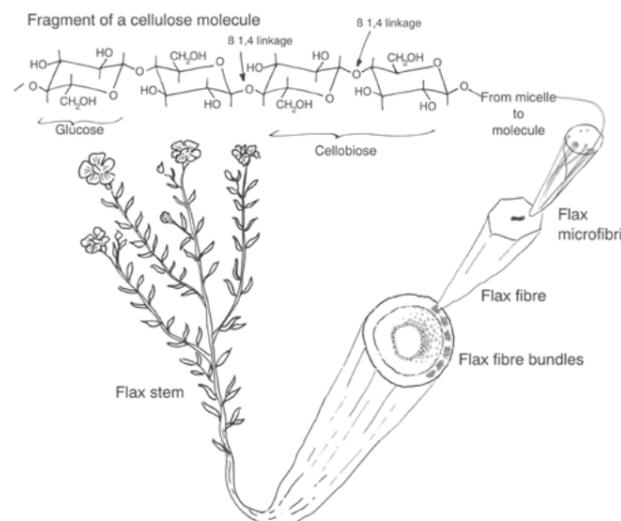


Figure 2: Schematic representation of the hierarchical structure of Flax (*Linum usitatissimum* L.) - from plant to cellulose (Müssig & Hughes, 2012).

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2. <https://allianceflaxlinenhemp.eu/en/european-flax-linen-hemp-media-library/27/ready-to-use-the-impregnated-fibre-bundle-test-ifbt>

1.3.2. Flax & Hemp Reinforcements Classification

In general, fibre orientation is very important for the resulting properties of the composite structure. Therefore, textile semi-finished products have been developed in which the fibres are already oriented as needed for the final composites. Two groups of semi-

finished products have been developed: “dry” (preforms) and “wet” (prepregs). These can be found on the online sourcing platform:

<https://allianceflaxlinenhemp.eu/en/sourcing-platform-home>.

PRODUCTS	THERMOPLASTIC PROCESS	THERMOSET PROCESS	APPLICATION AREAS
Reinforcements at cm-scale	LFT-D- ILC	Spray up	Automotive, electronics, aerospace, sports and leisure, consumer goods, medical, building, railway, wind energy
Reinforcements at dm-scale	Textile preforms	Textile preforms	Textile preforms
Powders and meals at μ m-scale	Injection moulding, stamping, extrusion, lamination		Automotive, electronics, sports and leisure, consumer goods, building, medical
Yarns, rovings	After cutting : Fibres in mm- or cm-scale - Textile preforms	Pultrusion, winding processes (incl. coreless)	Building, consumer goods, sports and leisure
Nonwovens	Thermo-compression	SMC, RIM, wet lay-up, infusion, RTM	Automotive, electronics, aerospace, sports and leisure, consumer goods, building, railway, naval, wind energy
Fabrics	Thermo-compression	RTM, infusion, wet lay-up, spray up, pultrusion	Aerospace, railway, naval, sports and leisure, wind energy
UD	Thermo-compression	RTM, infusion, wet lay-up, spray up	Aerospace, railway, naval, sports and leisure, wind energy
Multiaxials	Thermo-compression	RTM, infusion, wet lay-up, spray up	Aerospace, railway, naval, sports and leisure, wind energy
Compounds	Injection, extrusion, compression	SMC, BMC	Automotive, electronics, sports and leisure, consumer goods, building, medical

Table 2: Fibre types, processes and application areas. Source: Natural fibres and reinforcements Material solutions – FRD-CODEM

1.3.3. Flax & Hemp Composites Performance Range

Over the years, many studies have investigated the fibre volume fractions and mechanical properties achievable in Flax and Hemp composites. The following graphs help clarify the ranges of attainable performance for composites reinforced with UD preforms and tested in the fibre direction, both in terms of mechanical properties and fibre volume fraction.

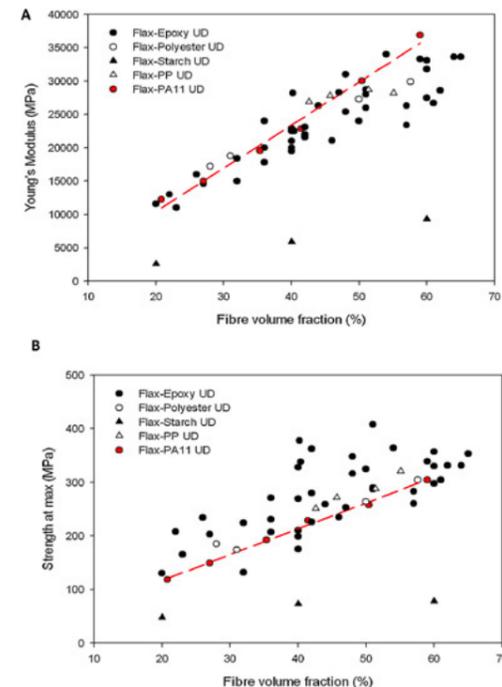


Figure 4: Young's modulus (A) and strength at max (B) of Flax-PA11 UD composite compared with literature data. The red dotted lines represent the linear regressions for flax-PA11 UD. Adapted from Bourmaud et al. (2016).

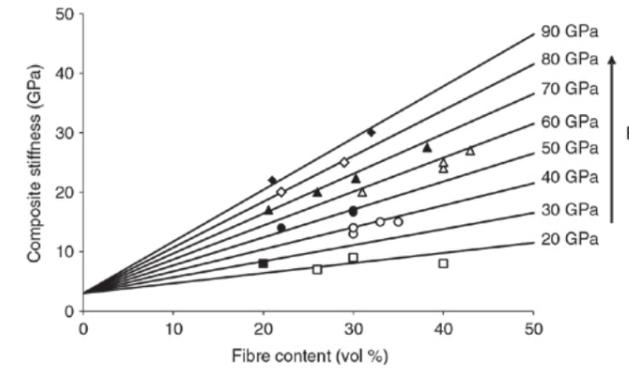


Figure 5: Data from literature on modulus (stiffness) of unidirectional bio-based composites. Lines are rules-of-mixtures model predictions with variable fibre stiffness from 20 to 90 GPa (Mehmood and Madsen, 2012).

Rule-of-mixtures lines are shown in a separate figure as reference trends to support interpretation of the literature data. Similar approaches for unidirectional biobased composites indicate that Flax- and Hemp-fibre composites can follow linear stiffness–fibre volume fraction relationships when fibre alignment and impregnation are well controlled.

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Bourmaud, A., Le Duigou, A., Gourier, C., Baley, C., 2016. Influence of processing temperature on mechanical performance of unidirectional polyamide II–flax fibre composites. *Industrial Crops and Products* 84, 151–165. <https://doi.org/10.1016/j.indcrop.2016.02.007>

Madsen, B., Brøndsted, P., Løgstrup Andersen, T., 2013. Biobased composites: materials, properties and potential applications as wind turbine blade materials. In: Brøndsted, P., Nijssen, R. (Eds.), *Advances in Wind Turbine Blade Design and Materials*. Woodhead Publishing, 363–386.

1.3.4. Drapability

Regarding the formability or drapability of fabrics, factors such as fabric areal mass, thickness, and in-plane shear, tensile and off-plane bending stiffnesses play an essential role. The fabric's stiffness depends on factors such as weave construction or needle density.

The distinctive feature of plant fibres is that the fibre bundles are discontinuous, unlike endless fibre reinforcements. The in-plane tensile stiffness of plant fibre reinforcements is much lower than that of continuous reinforcements. The stretchability of reinforcements improves their ability to conform to double-curvature shapes, which is especially important where deep-drawing is required.

A soft fabric takes the form of the mould but forms ripples, whereas a stiff one drapes away from the mould body, resulting in fewer ripples but with more inaccuracy.

On the level of the fibres, the following remarks are applicable, regarding

- **yarn stiffness:** high twisting increases the bending stiffness of the textile and hence decreases drapability and leads to a reduction in the Young's modulus and tensile strength of the composite;
- **linear density:** higher density decreases drapability;
- **fibre size:** increased thickness decreases drapability;
- **thread count:** higher density decreases drapability;

At the fibre scale, the low extensibility of Flax fibres makes them particularly suitable for controlling folds during composite manufacturing, especially in unidirectional fabrics. Owing to their limited tendency to spring back, they enable accurate shaping in complex geometries. In practice, up to one or two controlled folds can be introduced without inducing significant wrinkling or fibre damage, natural fibre provided that draping strategies such as localised heating, sequential lay-up, or mechanical assistance are applied. This behaviour facilitates reliable processing in components requiring tight corners and multi-axial shaping.

1.3.5. Permeability

Compared to synthetic fibres, plant-based fibres tend to absorb resins or model fluids and swell, which strongly affects flow characteristics during permeability measurement. As a result, the permeability of similar fabrics can appear lower when water-based model fluids are used than when a silicon-oil-based model is used. The fibre surface roughness, together with the composition of lignin, cellulose and hemi-cellulose of the outer layer, determines the wetting properties of the natural fibre, and may thus also affect permeability measurement, if performed in a transient manner. Francucci et al. found that natural fibres exhibit capillary pressures that are two or three times higher compared to synthetic fibres, elucidating the relevance of micro-flows and capillary effects occurring during impregnation. Some authors attributed this to the hollow structure of the fibres.

However, recent studies have shown limited evidence that the resin can impregnate the lumen since it is a closed cavity. Pantaloni recently reviewed the permeability of natural fibres and reported that, in general, Flax and Hemp textiles have a relatively high in-plane permeability, higher than that of glass reinforcement at similar fibre volume fraction, but with potentially larger capillary effects. Due to the potential swelling during tests, they recommend measuring permeability with the resin that will be used to make the composite, or with a fluid that has similar characteristics as the fluid (and not water-based).

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1.4. Handling Characteristics and Finishing Steps

1.4.1. Skin-friendly

Even though natural fibres are generally not harmful to the skin, appropriate protective equipment should be used during operations where dust may be generated. Vacuum systems must be equipped with **HEPA H13 or H14 filters** to ensure effective dust removal. Workers should wear a mask with a **P2 or P3 particulate filter**. Good ventilation, avoiding compressed-air cleaning, and using protective eyewear and gloves are also recommended to maintain safe working conditions.

1.4.2. Storage

Natural fibre fabrics have to be stored away from light and relative humidity levels above approximately 65–70% RH should be avoided, as excessive moisture can lead to bacterial or biological degradation. In normal indoor storage conditions (typical 30–60% RH), there are no specific risks, and a standard storage room used for fibres like glass or carbon works perfectly.

Under these conditions, untreated natural fibre preforms can be stored for long periods without issue. After transport or exposure to significant temperature or moisture variations, allow the preforms to stabilise for at least 24 hours before use.

Some low areal mass non-woven or unidirectional (UD) natural fibre preforms can be delicate and should be handled with care to avoid tearing.

1.4.3. Cutting

Natural fibres are tougher than glass or carbon fibres, so dedicated scissors should be used and not shared with more abrasive reinforcements in order to maintain cutting sharpness. Because their abrasiveness is low, cutting tools can be used for a long time without sharpening.



Figure 6: Examples of bad (a) and good cutting of Flax (b)

1.4.4. Edge Sealing after Composite Manufacturing

After composite manufacturing, the exposed fibre edges can facilitate moisture uptake, leading to fibre swelling and potential degradation of the fibre–matrix interface. For composites intended for outdoor or marine applications, it is therefore essential to seal the edges with a protective resin layer. Even in indoor environments, edge sealing is recommended to enhance the long-term durability of the composite.

1.4.5. Surface Finishing of Composites

A gel coat or an additional resin layer can improve surface smoothness and gloss while enhancing environmental resistance. After curing, any surface defects can be minimised by sanding, polishing, or applying protective coatings. These finishing techniques enhance the appearance and durability of natural fibre composites by reducing moisture and UV-induced degradation over time.

2 Managing Key Parameters & Defining Process Windows

Manufacturing methods and processing conditions have a major influence on the final properties of composites. In addition, Flax and Hemp fibres undergo changes in properties during processing, which must be considered.

The purpose of the following section is therefore to define process windows for the most critical parameters. It should be emphasised that these parameters are strongly interdependent. In particular, the interplay between temperature, processing time, pressure, and fibre moisture content has a decisive impact on composite quality. For instance, elevated moisture levels may induce porosity or weak fibre-matrix adhesion, especially when combined with high temperatures and prolonged cycle times.

2.1. Time-Temperature Effects on Flax and Hemp Composites

2.1.1. Thermo-kinetic Aspects

The time-temperature relationship must be carefully controlled to ensure proper resin crosslinking while minimising damage to the natural fibres.

In general, Flax fibres can withstand processing temperatures up to 180–190 °C for durations of 30–60 minutes without significant loss of mechanical properties. Above 200 °C, degradation of pectins and hemicellulose starts to affect fibre strength, and extended exposure at 220–230 °C can reduce tensile properties by more than 30 %.

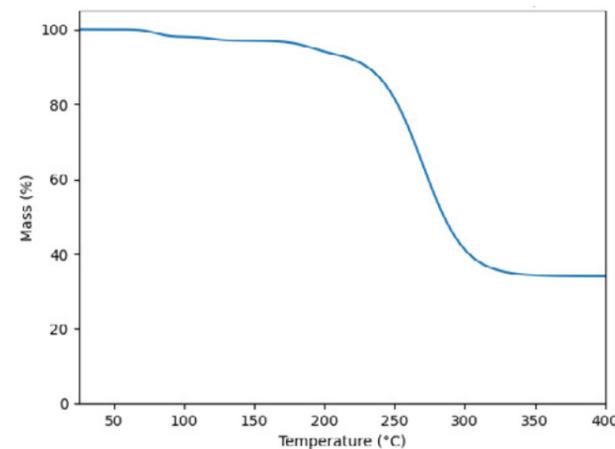
The main thresholds identified (Baley, 2006) are:

- Water liberation starting at 60 °C, vaporisation and exhaust of the absorbed water can occur
- Wax degradation at 120 °C
- Beginning of the degradation of pectins at 180 °C
- Beginning of hemicellulose and cellulose degradation at 230 °C
- Some time-temperature couples recognised as relevant limits are:
 - 160 °C - for 30 minutes of exposure
 - 200 °C - for 5 minutes of exposure

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Figure 7 shows a TGA diagram illustrating the degradation behaviour (mass loss) of Flax fibres as temperature increases, emphasising the need to carefully manage both thermal and temporal parameters during composite manufacturing.



- Moisture loss: up to 100–120 °C
- Onset of hemicellulose degradation: approximately 220–260 °C
- Main cellulose degradation peak: around 300–360 °C
- Lignin decomposition and remaining char: 400–550 °C

Figure 7: Illustrative TGA diagram of Flax fibres (based on Baley, 2006).

In some recent studies, fibres have been successfully processed with a PA6 matrix at 225 °C during very short compression-moulding cycles (~2 min) with minimal fibre degradation. Conversely, prolonged exposure at 105 °C, typically around 12 to 16 hours, has also been shown to induce damage (Baley 2012).

Liang et al. (2015) also demonstrated that at higher temperatures and longer processing times, Flax fibres undergo significant thermal degradation, which reduces the tensile strength of PA6-Flax composites from 90 MPa to 32 MPa when the processing temperature is increased from 230 °C to 250 °C and the cycle time from 2 to 5 minutes (see Figure 9). Tensile strength decreases with increasing temperature and processing time, with maximum values at low temperature and short consolidation time (≈ 230 °C / 2 min). The coloured contour lines represent strength levels and correspond directly to colours and data shown in the 3D view. This highlights the importance of controlling both temperature and exposure time to maintain composite performance in industrial processing.

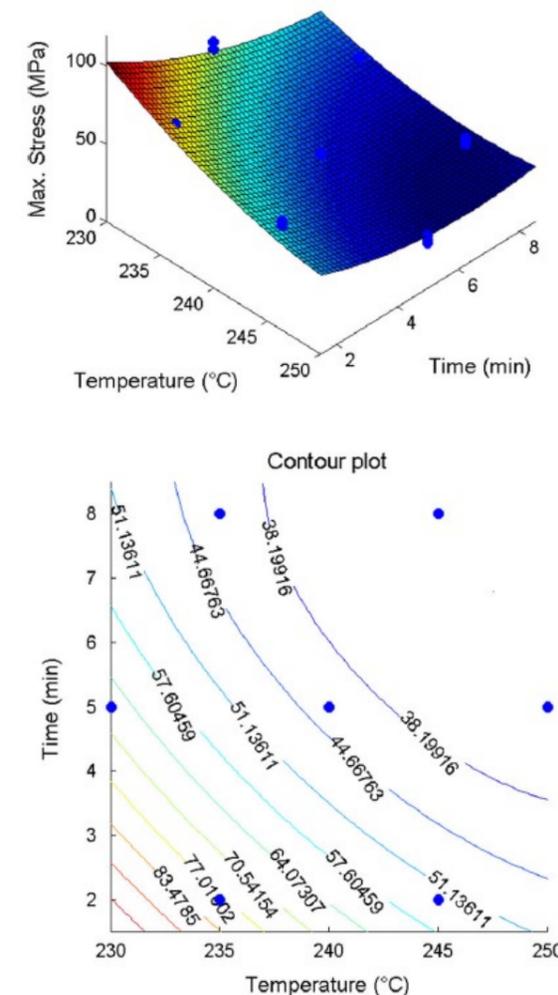


Figure 8: Thermo-compression forming of Flax fibre-reinforced polyamide composites: influence of the fibre thermal degradation on mechanical properties (Shaoyang Liang, Hedi Nouri, Eric Lafranche, 2015).

In this example, shorter processing times and the lowest feasible temperature led to the highest mechanical performance. Practically, users must also account for resin viscosity: too low impedes proper wet-out control, too high restricts penetration into the preform. Time, pressure, and temperature must therefore be balanced to ensure adequate impregnation while maintaining optimal mechanical properties.

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2.1.2. Matrix polymers and processing time-temperature coupling

POLYMER	DENSITY / g/cm ³	YOUNG'S MODULUS / GPa	TENSILE STRENGTH / MPa	FAILURE STRAIN / %	TG / °C	TM / °C	FAMILY	PROCESSING TIME	MOISTURE SENSITIVITY
Polyester (thermoset)	1.10–1.40	1.3–4.5	45–85	1–5	60–80*	—	TS	Medium (curing 15–60 min)	High sensitivity in standard cobalt-accelerated systems (risk of cure inhibition); improved tolerance with adapted accelerator systems
Vinyl Ester	1.10–1.35	3–4.5	60–90	2–6	100–130*	—	TS	Medium	Moderate > high sensitivity
Epoxy	1.20–1.40	2.1–5.5	40–85	2–7	80–120	—	TS	Medium to long (curing 30–120 min)	Low > Moderate Sensitive (moisture may affect curing kinetics and interfacial adhesion depending on hardener system)
Bio-based Epoxy	1.20–1.35	2.5–4.0	40–80	3–6	70–110	—	TS	Medium	Low > Moderate
HDPE	0.95–0.97	0.55–1.1	20–37	10–1200	-120	130	TP	Short (extrusion / injection)	Very high (hydrophobic)
PP	0.90–0.91	1.2–1.7	30–70	10–600	-10	160–170	TP	Short	Very high (hydrophobic)
PVC (rigid)	1.30–1.45	2.4–4.1	40–60	2–20	80	212	TP	Short	Low
PLA (biobased)	1.21–1.25	3.0–3.5	50–70	2–10	55–65	150–170	TP	Short	Moderate (hydrolysis risk)
PHB / PHBV (biobased)	1.18–1.25	3.0–4.0	30–45	5–8	0–5	160–180	TP	Short	Moderate (hydrolysis risk)
PA6 (Nylon 6)	1.13	2.5–3.0	60–90	30–60	50	220	TP	Short	High moisture uptake (hygroscopic)
PA11 (biobased)	1.02	1.5–1.8	45–60	40–200	45	190–195	TP	Short	High moisture uptake (hygroscopic)
Elium® (liquid thermoplastic acrylic)	1.15–1.20	2.5–3.5	50–100	2–10	~100	amorphous	TP	Medium (room-temp polymerisation)	Low Low sensitivity during polymerisation; thermoplastic behaviour above Tg.
PHA	1.20–1.25	2.5–3.5	25–40	2–8 (highly grade-dependent; can reach >20% for modified grades)	-5 to +5	160–180	TP	Short	Moderate
PCL	1.10–1.15	0.2–0.4	10–25	300–800	-60	58–65	TP	Long	Low to moderate

Table 3: Typical properties of different types of polymers.

Properties of different polymers. TP= thermoplastic / TS = thermoset (From “Flax and Hemp fibres: a natural solution for the composite industry” CELC, JEC, 2012, Matrix Polymers, Christophe Baley, Peter Davies)

* Values are indicative ranges for neat polymers or fully cured resins at room temperature. Mechanical and thermal properties strongly depend on formulation, grade, additive content, curing conditions and testing standards. For example, the failure strain of PA11 (Polyamide 11) can vary significantly with temperature, strain rate, plasticiser content or fibre reinforcement; therefore, there is no single fixed value applicable to all systems. Moisture compatibility refers to processing sensitivity (e.g., cure inhibition, hydrolysis or plasticisation) rather than long-term environmental durability. Tg values are formulation- and cure-dependent.

Thermoplastic composites

The effective processing window of a thermoplastic polymer is commonly defined in relation to its glass transition temperature (Tg) and its melting point (Tm). For semi-crystalline thermoplastic polymers, this window typically extends above Tm to ensure sufficient melt flow and consolidation without inducing thermal degradation or defects such as haze, bubbles, or excessive sagging. To process an amorphous thermoplastic polymer (which typically doesn't have a regular Tm), processing temperatures are typically up to 100 °C above their Tg to make the polymer flow sufficiently.

The processing window is governed by the material's thermal properties, the presence of plasticisers, the quality of the fibre-matrix interface, and the selected processing method (e.g., thermoforming, injection moulding).

Thermoset composites

For thermoset composites with natural fibres, curing conditions must be adjusted according to the specific resin system, as moisture tolerance varies between epoxies, polyesters, vinyl esters, and other thermosets. Moisture in the fibres can accelerate or inhibit curing, generate vapour, or create porosity. Regardless of the resin type, the exotherm must be managed to avoid temperatures that could degrade the fibres. Using lower-temperature or lower-exotherm formulations helps minimise this risk.

When curing above 100 °C, applying moderate pressure (e.g., in compression moulding) can limit porosity by increasing the boiling point of water. Tool self-heating should also be monitored, as local temperature peaks often exceed nominal settings and may damage the fibres. For polyester and vinyl ester systems, cobalt-free accelerators are likely necessary to avoid moisture-related inhibition.

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2.2. Moisture Management & Void Content

Before processing, Hemp and Flax fibres absorb moisture from the surrounding environment, with equilibrium levels governed by ambient relative humidity. As illustrated in Figure 10, the moisture adsorption and desorption behaviour of natural fibres at 25 °C shows a clear dependence on fibre type. While voids facilitate moisture ingress, their primary impact is a degradation of mechanical performance. Void content strongly depends on the manufacturing method and processing parameters and should therefore be minimised through appropriate process selection. For example, resin transfer moulding (RTM) generally produces lower void contents than hand lay-up.

Regarding swelling, in a composite material reinforced with Flax or Hemp fibres, fibre swelling induces internal stresses in the matrix, which can lead to a loss of fibre-matrix adhesion and long-term cracking. Fibre swelling is therefore a critical factor to consider (Said, 2024), as it involves changes in fibre geometry.

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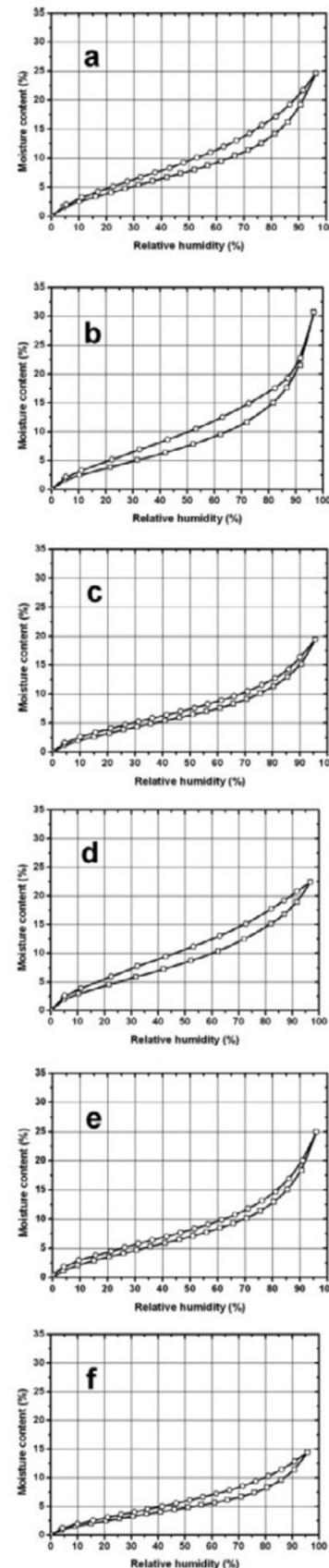


Figure 9: Moisture adsorption and desorption behaviour for jute (a), coir (b), Flax (c), Sitka spruce (d), Hemp (e), cotton (f), at 25 °C (Hill, C.A.S., Hughes, M., 2010. The water vapor sorption behaviour of natural fibres. *Journal of Applied Polymer Science* 116, 2166–2173).

2.2.1. To dry or not to dry, that is the question...

Drying...

It is possible to pre-dry natural fibres to eliminate moisture, reduce their mass, and prevent chemical interactions between water and resin (e.g., with polyester resin). Drying natural fibres before processing can be relevant in specific cases, particularly when fibre layers are trapped inside the composite, where residual moisture can persist and cause defects (porosity, reduced mechanical properties).

...or not

A dried natural fibre will re-swell when exposed to moisture, which can locally degrade the fibre-matrix interface and cause whitening at the composite surface. Excessive drying can also damage intrinsic fibre components, such as pectins, thereby reducing mechanical performance. In most cases, drying offers limited benefits relative to its time and energy cost; controlling storage conditions is often more efficient. When the matrix tolerates some humidity, not drying the fibres can even be advantageous, reducing energy use and improving long-term durability, since pre-swollen fibres are less susceptible to further moisture uptake in service.

The key parameter is the fibre water content, which depends on ambient humidity, temperature, and fabric architecture. Different weaves or areal mass can exhibit different moisture uptake under identical storage conditions. At an industrial scale, humidity control can be achieved by adapting simple systems, such as salt-based chambers (*where the presence of salt controls the humidity in the air*), to larger storage areas. Knowing the sorption curve of each reinforcement (or obtaining it from the supplier) helps predict moisture content at processing. In resin infusion production processes (such as RTM or VARI), operators must adjust infusion speed and monitor the resin-flow / moisture-content relationship to keep the process within a stable window.

Recent tests on 2/2 twill Flax (300 g/m²) show that resin infusion remains stable at moderate fibre moisture levels (5–7 mass%), with reductions in stiffness (≈ 8 GPa) and strength (≈ 130 MPa) compared to dry fibres. Above 10 mass% moisture, resin pressure may exceed compaction stress, causing fabric slippage and significant performance losses (≈ 6 GPa, < 130 MPa). Optimal infusion is obtained at a capillary number around 10^{-3} , which minimises porosity; higher flow rates combined with elevated moisture greatly increase the risk of defects (J.-B. Jouenne et al., ICCM24, Baltimore).

3. <https://bionics-group.com/>

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2.2.2. Moisture Sensitivity as an Opportunity for Innovative Applications

Moisture is not necessarily a constraint, as water molecules can act as lubricants, facilitating the forming and shaping of composite preforms into complex parts. Moreover, the hygroscopic nature of natural fibres can be leveraged as a design advantage for hygromorph materials; for example, see the work of Antoine Le Duigou's [team](#) at IRDL, Université Bretagne Sud³.

Flax and Hemp fibres exhibit anisotropic dimensional changes due to temperature changes, characterised by very low longitudinal dimensional expansion ($\approx 1.2 \times 10^{-6}$ /K for Flax) and much higher transverse expansion ($\approx 75 \times 10^{-6}$ /K), the latter being strongly influenced by moisture content.

The hygroscopic response induces moisture-driven dimensional variations that primarily affect the transverse direction. When properly managed through appropriate processing and moisture control, these dimensional changes can be accommodated without detrimental effects, thereby supporting the use of Flax and Hemp fibres as low-density and sustainable composite reinforcements.

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2.3. Pressure and Compaction

Flax reinforcements behave quite similarly to other fabrics, except for compaction and permeability, where their response curves differ significantly (see below).

2.3.1. Influence of the Fibre's Architecture

Flax fibre reinforcements exhibit relatively low initial packing density due to their irregular cross-section, lumen structure and yarn architecture, leading to significant thickness reduction under compaction. In liquid composite moulding (LCM) processes such as infusion or RTM, increasing compaction reduces permeability and may hinder resin flow, making impregnation control critical.

Their hygroscopic nature further affects compaction behaviour, as moisture uptake can induce fibre swelling prior to processing. Compared to glass or carbon fabrics, natural fibre fabrics generally show greater variability in nesting and transverse compressibility, making high fibre volume fractions more process-dependent.

In infusion-type processes, fibre volume fraction is often limited by permeability constraints. Higher values ($\approx 45\%$ or above) are more readily achieved in RTM with controlled mould closure or in compression moulding, provided fibre damage and excessive porosity are avoided.

2.3.2. Coupling Pressure and Time rather than considering Pressure alone

Processing natural fibre composites requires adapting parameters to the morphological and hygroscopic characteristics of Flax and Hemp (See Figure 11). Consolidation behaviour is strongly process-dependent, and pressure ranges must therefore be specified accordingly.

In liquid composite moulding (LCM) processes such as infusion or RTM with thermosets, compaction pressures are typically limited to ~ 0.5 MPa (vacuum and mould clamping). This constrains the achievable fibre volume fraction, making porosity control critical: beyond a certain compaction threshold, permeability decreases sharply, leading to incomplete impregnation and increased porosity rather than higher fibre content.

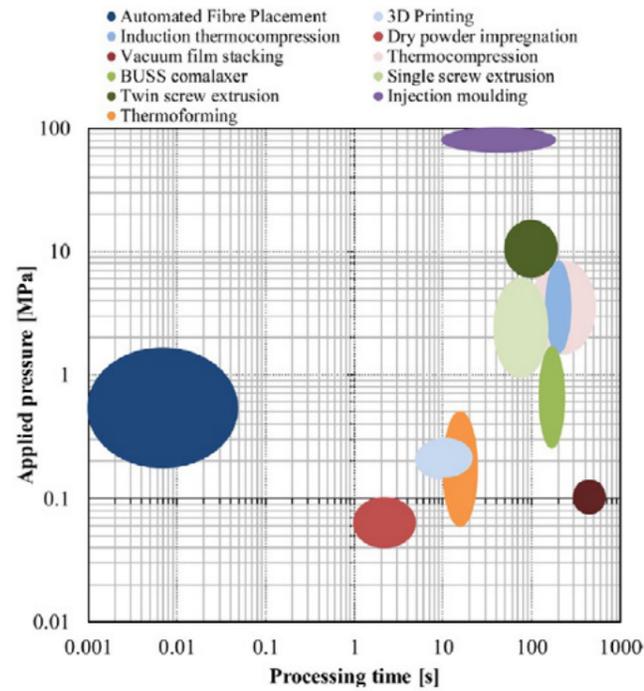


Figure 10: Range of applied pressures and processing times conventionally used for various bio-based composites processing techniques. Property changes in plant fibres during the processing of bio-based composites (Bourmaud et al., *Industrial Crops & Products* 154 (2020) 112705).

In contrast, compression moulding of thermoset prepreps or thermoplastic composites involves several MPa. Higher fibre volume fractions can then be achieved, and fibre flattening may improve packing efficiency, provided excessive pressure does not induce fibre crushing, misalignment or matrix starvation. In all cases, consolidation pressure governs the balance between fibre volume fraction and porosity, but this balance remains process-specific (See Figure 12).

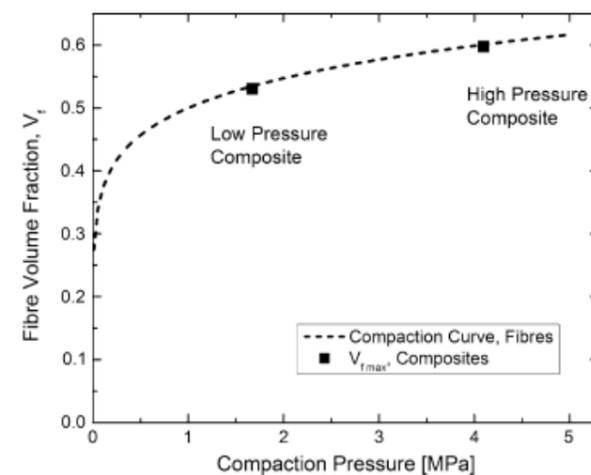


Figure 11: Compaction curve for a unidirectional Flax yarn assembly together with values of V_{fmax} for the unidirectional Flax/PET composites manufactured by low and high consolidation pressure (Aslan M., Mehmood S., Madsen B., 2013. Effect of consolidation pressure on volumetric composition and stiffness of unidirectional Flax fibre composites. *J. Mater. Sci.*, 48, 3812–3824. <https://doi.org/10.1007/s10853-013-7182-3>).

Fabric architecture further influences compaction without any universal hierarchy. Non-crimp fabrics, woven fabrics and needle felts respond differently depending on crimp, nesting and initial packing density. Yarn twist also affects compressibility: highly twisted yarns are rounder and less compressible than low-twist yarns.

Moisture and resin content significantly modify compaction behaviour. Wet or impregnated fabrics compact more easily, but fibre swelling affects the achievable fibre volume fraction; moisture must therefore be controlled.

Thickness variability is often governed by the mechanical compliance of the forming system (press, tooling and load chain) rather than sensor accuracy, as elastic deformation under load alters effective compaction. Load-controlled closing may induce thickness variations, while displacement-controlled closing can generate excessive forces if poorly calibrated. Good parallelism, assessment of system stiffness and appropriate selection of closing mode are essential.

Edge preparation and compaction rate also influence quality. Natural fibre fabrics are prone to fraying, particularly along cuts parallel to fibres, critical in RTM with central injection. Rapid mould closing increases peak forces and damage risk, whereas progressive loading allows relaxation and reduces defects.

Indicative consolidation pressures range from 150–700 kPa for dry non-crimp fabrics and 60–220 kPa for woven fabrics, decreasing when wet or pre-impregnated. These values remain approximate, as optimal pressure depends on architecture, areal mass, yarn type and moisture content (See Figure 13).

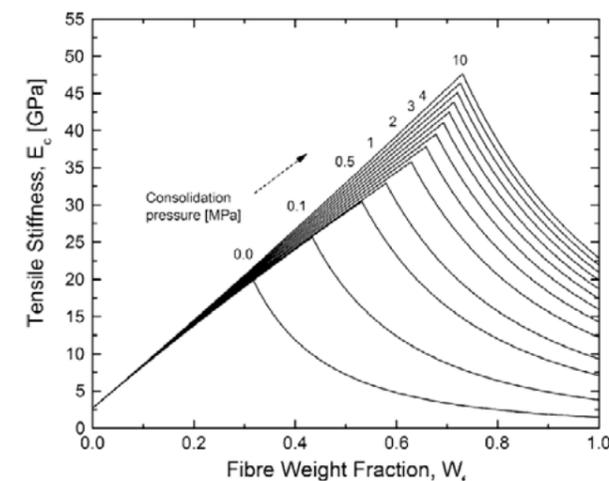


Figure 12: Property diagram showing model calculations of stiffness as a function of fibre mass fraction for Unidirectional Flax/polyethylene terephthalate composites manufactured with different consolidation pressures in the range 0–10 MPa (Madsen B., Aslan M., Mehmood S., 2013. Effect of consolidation pressure on volumetric composition and stiffness of unidirectional Flax fibre composites. *J. Mater. Sci.*, 48, 3812–3824. <https://doi.org/10.1007/s10853-013-7182-3>).

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3 Conclusion

The first sections of this guide show that manufacturing high-performance Flax and Hemp composites requires treating materials and processing parameters as an interconnected system. Fibre architecture, moisture content, temperature, pressure and processing time are tightly interdependent, and controlling their interactions is essential for defining a stable process window and ensuring repeatable industrial quality.

A combined **multi-scale and multi-physics approach**—linking fibre behaviour, reinforcement architecture, moisture transport, heat transfer and mechanical response—is key to understanding and mastering these interactions. **This expertise is well represented among our members, who support industrial development across the full value chain, from fibre, to semi-finished product suppliers, processors and technical centers, those European companies drives support and solutions, serving as a bridge between the requirements of the multi-segment industry for technical Flax and Hemp applications.**

The next document will build on this foundation by detailing selected manufacturing processes, highlighting the specificities of natural fibres, common issues, and practical guidelines for robust implementation.



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About



The Alliance for European Flax-Linen & Hemp is the only European agro-industrial organization that serves as a global reference and brings together all players in the European Flax-Linen and Hemp value chain.

A platform for reflection, market analysis, dialogue, and strategic orientation, the Alliance for European Flax-Linen & Hemp presides over an industry of excellence in a globalized context. It encourages dialogue with national and European public authorities.

The Alliance for European Flax-Linen & Hemp creates an environment that fosters competitiveness of industrial businesses as part of its three-fold mission of informing members, brands, and consumers, supporting the European ecosystem and European expertise, and promoting European Flax-Linen and Hemp as the preferred sustainable premium fibres worldwide.

It connects 10,000 businesses in 16 European countries and bases its work on the values of solidarity, innovation, scientific validation, and respect for people and planet.

It promotes, initiates, and organizes strategic reflections and research on its fibres to be able to provide all of its interlocutors with evidence-based economic data, environmental information, and reliable scientific evidence.

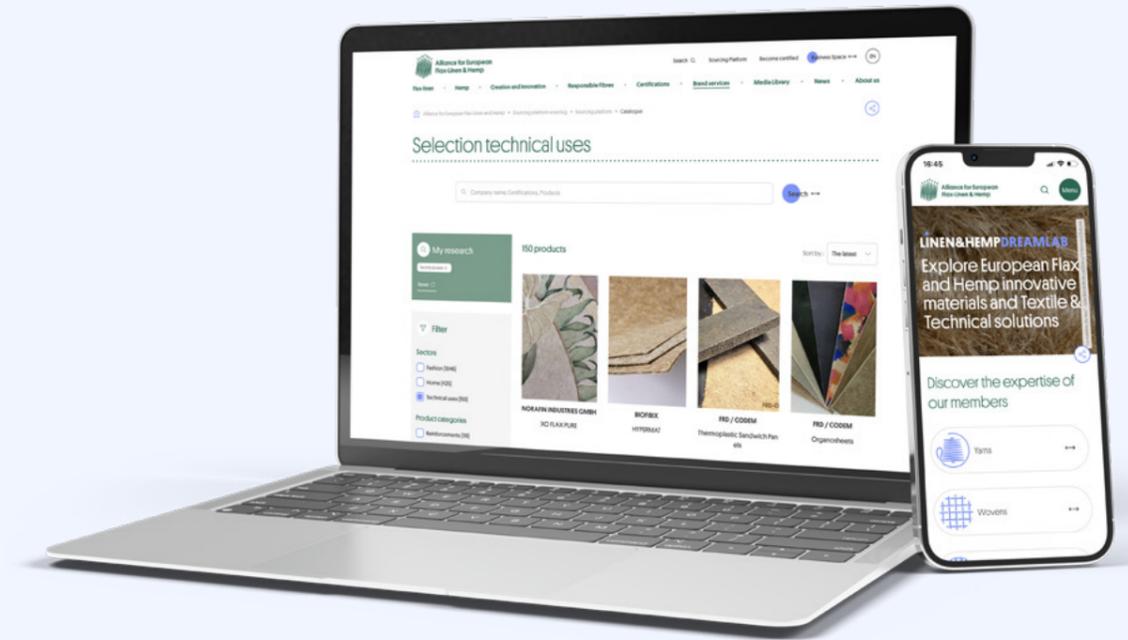
The Alliance for European Flax-Linen & Hemp strives to increase the international visibility of its fibres, whose technical and environmental properties inspire global creation and open new opportunities for industrial innovation. It guarantees the traceability of Flax fibre thanks to the Masters of FLAX FIBRE™ and Masters of LINEN™ certifications.

With its Technical Section, Alliance for European Flax-Linen & Hemp helps its members move towards the future to discover new opportunities such as high-performing composite products. This Section brings together fibre and semi-finished product suppliers, preparers and processors, serving as a bridge between the requirements of the multi-segment industry and the value chain's industrialization capacity for technical Flax and Hemp applications.

The Alliance for European Flax-Linen & Hemp is the new name of the CELC, an association founded in 1951. Western Europe is the number one Flax-producing region in the world [France, Belgium, and the Netherlands account for 3/4 of production].

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About the Enlarged European Scientific Council

The mission of the European Scientific Council is to support the activities of the Alliance to improve the market position of Flax & Hemp fibre composites and thus bring scientific knowledge to end-users. The experts work together according to their specializations and topics.

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