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Flax and Hemp fibres: a natural solution for the composite industry

CELC

JEC COMPOSITES

Flax and Hemp fibres: a natural solution for the composite industry

Prepared for

By

15 rue du Louvre - 75001 Paris - France
Tel: +33 (0) 1 42 21 02 35 - www.mastersoflinen.com

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25 Bld de l'Amiral Bruix - 75116 Paris - France
Tel: +33 (0) 01 58 36 15 00 - www.jeccomposites.com

Preface

At a symposium I attended in North America recently, someone from Ford mentioned that as early as the 1940s, Ford was using hemp fibre reinforcement for automotive parts.

We could even follow the trail of plant-fibre reinforced composites all the way back to ancient times, when plant fibres were often used to reinforce building materials such as sand, earth, or clay.

Over the past few decades, technical flax and hemp fibres have penetrated sectors in the Northern Hemisphere as varied as building & construction, air, ground and sea transportation, industry, and sports & leisure, among others. There has been a lot of progress, and of course we wound up creating a Biocomposites category in all the different JEC Awards programmes in Europe, Asia and America. Each year, a large number of plant-fibre-based entries are received.

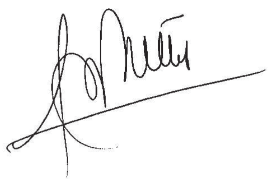
These days, a week doesn't go by that there isn't a plant fibre conference held somewhere in the world. Information about this sector is essential. We need to talk about the advances made in plant-fibre production and converting processes. The current issue is how to industrialize this composite segment, how to ensure consistent quality at a large scale at an acceptable price.

It came naturally that two organizations as complementary as the European flax and hemp confederation CELC and JEC should pool their expertise to treat such a subject. CELC contributes its knowledge of plant fibre markets, which is second to none, and JEC offers its expertise as an information provider and the reach of its international network of 250,000 composite professionals.

Our compliments to CELC for the excellence of our partnership. My special thanks to Benoit Savourat, President for CELC Technical Division and Marie-Emmanuelle Belzung, CELC Secretary-General.

We hope that this book will do so much to advance the use of flax and hemp fibres in composites that we will soon need to update it!

Frédérique Mutel
President & CEO
JEC Group



CELC is dedicated to creating a competitive environment for industry.

Natural flax and hemp fibres are European renewable resources with mechanical advantages that are ideal for sustainable innovation. These two fibres multiply the eco-design potential of new composite materials and, for designers and industrial engineering & design departments, give new impetus to the research and development process.

By creating favourable conditions for new solutions and guiding its manufacturers towards the future, the European flax and hemp industry is in the forefront of this dynamic growth-by-innovation process.

CELC, the European Flax and Hemp Confederation's Technical Section has a commitment to anticipate the needs and regulatory constraints, and to respond practically to the specific requirements of the industry in each of the application sectors. Its innovative materials platform takes an “open innovation” approach in order to harness initiatives and expertise in a trio of unique skills, by pooling the resources of the agro-industrial chain, the network of research scientists, and the companies that are tuned into customer expectations.

The synergy between flax and hemp goes well beyond their traditional fields of application, and these fibres of the future reveal their multifaceted performance in the composite industry.

Marie-Emmanuelle BELZUNG
Secretary General of the CELC

CELC is dedicated to creating a competitive environment for industry.

By creating the CELC Technical Section in 2005, the flax and hemp industry pledged its commitment to an active policy of research and innovation dedicated to composite materials.

Our expertise in the production of natural fibre reinforcement has progressed continuously, thanks to a technological watching-brief based on developing and sharing technical and scientific knowledge. In less than a decade, our expertise has been considerably strengthened through feedback from the industry.

As part of this continuous pooling of expertise, this publication formalises the close collaboration between the CELC's European Scientific Committee and our industry's R&D teams. This scientific and technical research network reinforces our conviction that these fibres are by nature equally reliable for industrial purposes.

Today, our European fibres provide solutions for materials with high potential, opening the way to tangible eco-composites and providing an operational response to the environmental efforts of industry. The heart of our development strategy, is based on applying the potential of our research and putting to advantage the results gained, in order to enrich the design potential of our industrial partners.

With other industry players we have taken up this shared challenge of innovation along with enhancing business competitiveness.

Benoît SAVOURAT
President of the CELC
Technical Section

ADEME, the French Environment and Energy Management Agency

In France, the 2007 Grenelle Environment Forum set some bold objectives to combat climate change, secure the energy supply, protect health and the environment, and develop a green economy.

Reaching these objectives will entail radically changing the ways we produce and consume. Replacing the limited and GHG-generating fossil fuel resources with renewable energy and materials will be one of the major challenges as our businesses make the transition. In this respect, agri-sourced products, more specifically natural fibres like flax and hemp, constitute excellent opportunities.

The scope for research is huge. We must reinvent many of the products and processes and create new industrial chains to guarantee that these new activities are economically viable. At the same time, we must be able to control the life cycle of these innovations and maintain a good balance in land use and between dietary and energy uses for biomass.

The purpose of the French Environment and Energy Management Agency (ADEME) is to promote such projects and provide financial support for R&D programmes and marketing/ environmental impact studies. It also plays a role in structuring the natural fibre value chains by bringing the players together, including research scientists, technologists, fibre producers, processors and users, associations, builders and technical centres. Support for the innovations from these value chains is also provided through the actions of the European "Lead Market Initiative". One of the Initiative's objectives is to ensure consistent development of the European market for bio-sourced products.

The interest in natural products and fibres is growing. We need more research programmes in order to make these materials more functional and competitive. The challenge is not just technological, but also societal, in that we must demonstrate that these natural resources provide the right solutions for sustainable consumption.

François LOOS
President of the ADEME

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Contributors, the European Scientific Committee of CELC

To further the strategic foresight for technical uses, the CELC's Technical Section created a European Scientific Committee in 2009, dedicated to flax and hemp fibres used as composite reinforcement.
Under the Open Innovation initiative, 10 experts from five different countries are sharing their knowledge of analytical and characterisation techniques to define innovations, in anticipation of industrial requirements.
With this publication of reference, the European Scientific Committee transfers its knowledge to the whole chain value of the composite industry.

BELGIUM

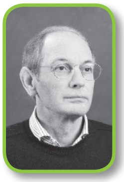
Professor Dr. Ir. **Ignaas VERPOEST** started the polymer composites research at the Department of Metallurgy and Materials Engineering of the Katholieke Universiteit Leuven in 1982. As a full professor (since 1991) he is coordinating the Composite Materials Group, consisting of 10 postdoc and project researchers and 25 PhDstudents, working in research areas like textile based and nano-engineered composites, natural fibre composites and process and product development for composites. Prof. Verpoest was President of the European Society for Composite Materials (ESCM) and of the International Committee on Composite Materials (ICCM).
He serves now as President of the European Scientific Committee of CELC.

Joris BAETS is Postdoctoral Researcher at KU Leuven, Department Metallurgy and Materials Engineering. He is also the coordinator of the CELC's European Scientific Committee, and is working on the use of flax and hemp fibres in composites, the optimisation of preforms made of these fibres, and the search for potential applications.

Professor **Joris VAN ACKER** is head of the Laboratory of Wood Technology at Ghent University. His team is active in the anatomical and chemical study of natural fibres and their chemical (pre)treatment. Further research includes moisture dynamics and biological durability of natural fibre composites.

DENMARK

Hans LILHOLT is Chief Scientist at the Materials Research Division, Risø DTU, Denmark. His research areas include composite materials based on metals and polymers with inorganic, organic and natural fibres; mechanical properties and microstructures of metals and composites; process technology and fabrication of composite materials and components; and composite materials based on renewable resources, cellulose fibres and biopolymers.

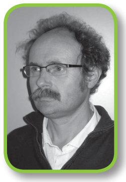


FINLAND

Mark HUGUES is Professor of Wood Technology and head of the Wood Material Technology group at the Department of Forest Products Technology, Aalto School of Chemical Technology. His current work focuses on lignocellulosic fibre reinforced composites, with emphasis on fibre-matrix interactions, material behaviour and fibre modification.

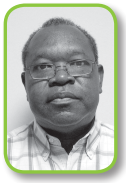
FRANCE

Christophe BALEY is Professor at the University of Bretagne Sud, LIMAT^B (materials engineering laboratory of Bretagne), at Lorient, France. Since 1991, he has been working on natural fibre reinforced polymers, specifically those with an organic matrix. He studies the mechanisms of plant fibre reinforcement of polymers.



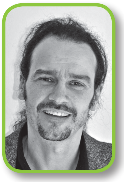
Peter DAVIES is Research Engineer at the French Ocean Research Institute IFREMER in the Materials and Structures group, located in Brest, France. His activities are centred on the mechanical behaviour and durability of fibres, composites and adhesives in a marine environment.

Moussa GOMINA is Research Scientist for the CNRS Crismat Laboratory at the national school of engineering Ensicaen in France. He works on the development of composite materials based on ceramics and biopolymers with synthetic or lignocellulosic fibres; functional materials (superconducting and thermoelectric ceramic oxides); and microstructural analysis and correlation with thermomechanical properties.



GERMANY

Since 2007 **Jörg MÜSSIG** is Professor of Biological Materials at the Hochschule Bremen - University of Applied Sciences, Bremen, Germany. He obtained his degree in Mechanical Engineering at the University in Duisburg, Germany in 1995 and his doctorate from Bremen University in 2001. After graduating in 1995 he joined the Faserinstitut Bremen e.V. – FIBRE – where, between 2001 and 2007 he was the leader of the department 'Bio-based Materials/Sustainability'. His main current research topics are the development of concepts for sustainable materials, bio-inspired materials, natural fibres & natural fibre composites as well as adhesion & interphases.



Gerhard ZIEGMANN is Professor Dr. Ir at the Institute for Polymer Materials and Plastics Processing, Clausthal University of Technology, in Germany. He works on natural and manmade fibre composites and the surface modification and processing of composites.

By drawing on the operational advice of those experts, the objective is to support the flax and hemp industry by increasing expertise in:

- standards and ranking
- training
- publication of reference works
- information sharing

They pool their knowledge of analytical and characterisation techniques to:

- establish an inventory of existing scientific resources and techniques
- consider possibilities for development and new research in correlation with the industry's strategy
- give priority to open-ended innovation and facilitate shifts of technical competences.

- I - A general introduction to composites, highlighting the advantages of flax & hemp composites

Ignaas VERPOEST,
Professor at the Department Metallurgy and Materials Engineering,
KU Leuven, Belgium
President of the European Scientific Committee of CELC

1. Designing (with) materials

If a designer wishes to shape the world around us, then he needs to impart a **form** to a **material**, so that a particular **function** can be performed. But a single function does not unequivocally determine the choice of a single material. Even a simple chair, a specific way of realising the function of 'sitting', can be found in all kinds of materials: wood, iron, wickerwork, plastic, aluminium, textile… and every possible combination of those materials.
The designer's creative process takes place within the **triangle of form-function-material.** The **form-function link** is the least problematic.

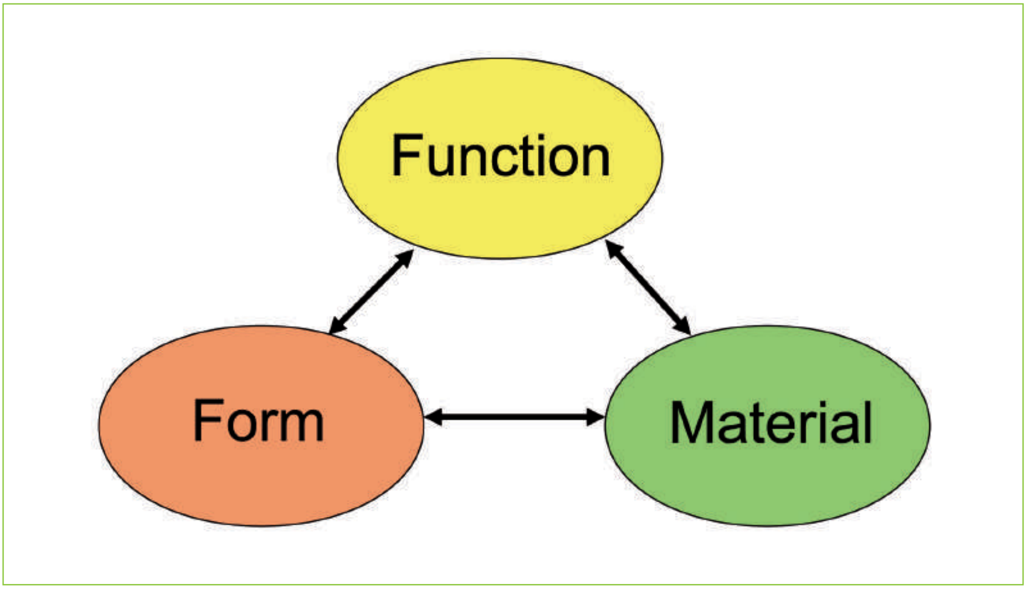


Figure 1: The 'designer' triangle.

The form-function relationship is closest to people's everyday experience, and hence doubtless to that of the designer. The link with materials, however, is less obvious. Not all forms are feasible, and a material may impose severe limitations on form.
And the least obvious link is that between **material and function.** The function first needs to be analysed, translated and often split down into a number of principal and subsidiary functions: a chair needs to be made so that you can really sit on it, but must not be too heavy; it may need to be stackable or foldable, or it may need to stay permanently outdoors. All these requirements can be linked to one or more **material properties.**

2. Materials and functionality

Functions have to be translated into material properties. Material scientists further divide these properties into mechanical, **physical, chemical and 'other' properties** (e.g. cost or availability). The **chemical** properties naturally include resistance to damage by chemicals, as well as by water (rust) or light (UV resistance). **Physical** properties are far more diverse, but usually have to do with some form of conductivity or penetrability: electrical conductivity, transparency to light or X-rays, heat or noise insulation properties, and so on. In addition, there is a series of physical properties relating to a 'state'; for example, iron can be permanently magnetic, and has a high thermal capacity and a high specific weight. The latter property in particular is important for many designs.

However, the first properties that a designer has to contend with are usually the **mechanical** properties, and in particular stiffness and strength. Stiffness and strength are not synonymous, and are in fact not related to one another at all: the fact that a material is stiff does not automatically make it strong, and vice versa.

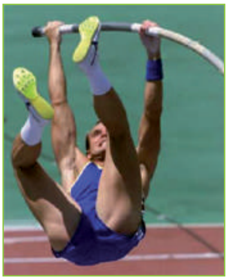


Figure 2: A composite with well-controlled stiffness: a vaulting pole.

The term ‘stiffness’ refers to the way a material reacts to a mechanical stress: the material starts to deform. If this deformation disappears again once, the stress has been removed; it is ‘reversible’ or ‘elastic’. However, if the deformation remains, it is ‘plastic’. The boundary between the two is the limit of elasticity or the yield point.

With a stiff material, a strong force is needed to achieve a given (elastic) deformation, and vice versa: a steel girder over a stream will give far less when you walk over it than a wooden beam with the same dimensions; while if the bridge is made of plastic, you may well end up with wet feet.

Figure 3: A wooden beam over a brook: not very stiff, but sufficiently strong to withstand the weight of one person.

Strength is not just about breaking, but often also has to do with resistance to permanent deformation. Confusingly, in most construction materials, stiffness and strength have little or nothing to do with one another. All types of steel are equally stiff, but their strength can vary enormously. The steel wire in radial tyres (a hard-drawn, high-carbon steel wire) is some ten times stronger than the soft, low-carbon steel wire used, for example, to tie flowers together, and yet they have the same stiffness. The same is true of aluminium alloys and many other metals, and of ceramic materials.

Figure 4: Picture of a broken carbon fibre composite tensile test specimen.

The microscopic processes that determine strength, especially the development of permanent, plastic deformation or the growth of cracks until the material breaks, are completely different from the physical principle that determines stiffness.
Stiffness is determined by the atomic or molecular structure of materials. A solid behaves like a solid because the atoms or molecules from which it is made are attracted to one another and hence keep one another in a fixed position. If these forces of attraction or 'affinities' are intense, it will be difficult to stretch the material a little, to deform it elastically. In this case, it is a stiff material. But if the mutual affinities are weak, the result is a floppy or flexible material.

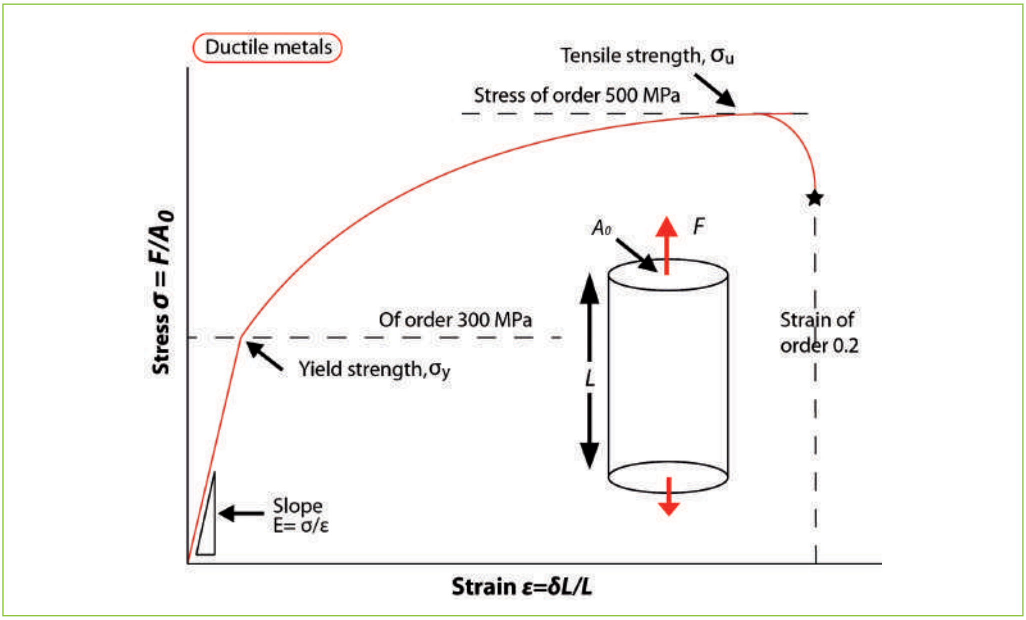


Figure 5: Stress-strain curve of a typical construction material (ductile metal), indicating the meaning of stiffness E and strength σ_u (from M. Ashby et.al., Materials, Butterworth-Heinemann, Oxford, 2007)

Metals and ceramic materials are held together by intense affinities between the atoms (primary bonds[1]) and hence are usually stiff materials. However, things become interesting when a material has both stiff primary bonds and loose secondary bonds present in it. This is the case with polymers, which are made up of long strands (chains) of atoms linked by primary bonds. These chains are in turn connected to one another by loose secondary bonds.[2]

So will the material be stiff or weak? In the case of ordinary polymers, the weakest link – the secondary bonds – will be decisive: polymers are flexible materials, compared with metals. This is true of the 'artificial' polymers or synthetic materials (also called 'plastics') such as polypropylene, nylon, plexiglas and so on, but also of natural polymers such as wood, flax, cotton or spaghetti. The difference in stiffness from metals is fairly great: around ten to a hundred times less.

1 Basic chemistry: primary bonds are metallic, ionic or covalent, while examples of secondary bonds are Vanderwaals or hydrogen bonds.
2 Later on we shall see that there are two types of polymer, thermoplastic and thermosetting, and that primary bonds also arise between the chains in thermosetting polymers (see also Chapter 4 on matrices).

3. Why is weight important?

To be able to compare materials with one another, we use the weight (or to be more precise, the mass) per unit volume, also called the specific mass, or often for the sake of convenience, the specific weight or density (kg/litre or kg/dm^3). Metals such as steel, copper and aluminium are heavy, while polymers are light.

Why is one material lighter than another?
In simplified terms, this is related to two factors: the atoms from which the material is constructed (iron atoms are heavier than the carbon and hydrogen atoms from which polypropylene is constructed), and of course the number of atoms present in a unit volume of material: the more densely the atoms are packed together, the more atoms per unit volume and hence the heavier the material. And this is a second reason why plastics are so light: the strands or chains are only connected with loose (secondary) bonds, and are not attracted closely together, and hence result in a material with a low average number of atoms per unit volume.

Weight is important, first and foremost for an obvious economic reason. Materials are bought by the kilogram. A kilogram of plastic is approximately the size of a one-litre milk carton, but the volume of a kilogram of steel is only the size of a small yoghurt pot (1/8 litre!).
However, there is a more fundamental reason inspired by **ecological** considerations. Lighter structures consume less energy, especially in the case of moving objects. This is obvious for anything that seeks or needs to defy gravity by its own strength, like aircraft.

(Source: *Museeuw Bikes*)

Figure 6: A composite F1-race car and a composite bike. Both need to be as light as possible, in order to reduce energy consumption.

But objects which need to be **accelerated** or slowed down also benefit from having the lowest possible mass: cars, bicycles, tennis rackets and so on. The reasoning is simple: energy consumption is proportionate to the product of mass and acceleration. And finally, of course, anything that has to be lifted needs to be as light as possible: chairs, irons, lift cables, and so on.

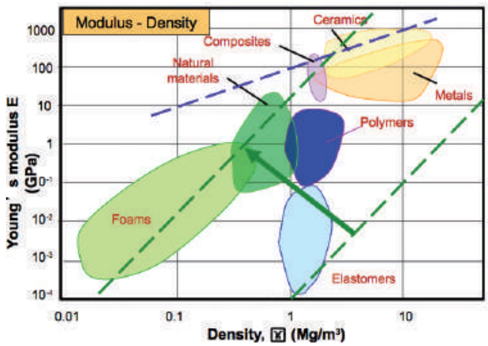


Figure 7: The Ashby-type diagram for comparing materials: stiffness versus density. The blue line shows materials with equal specific stiffness E/ρ the green line shows materials with equal specific stiffness for plate bending or buckling $E^{1/3}/\rho$ (the scales in the graph are logarithmic) (based on M. Ashby et.al., Materials, Butterworth-Heinemann, Oxford, 2007)

4. Strong, stiff and light

A designer who wishes to design light products clearly faces a dilemma. He can opt for a light but usually flexible material (polymers or plastics), or for a heavier but stiffer metal. To which property should he attach the most importance? On the basis of mechanics, it can be demonstrated that if one wants as light a product as possible, **the stiffness (E) divided by the specific weight (ρ) must be maximised.** The quotient E/ρ (also called the specific stiffness) needs to be as high as possible. This can be achieved by choosing a material with a high stiffness E, or with a low specific weight ρ. Interestingly, the two material characteristics turn out to offset one another to some extent[3]: iron (or steel), aluminium, titanium, etc. all have a specific stiffness of approximately 26 GPa/kg/dm³. Plastics, however, achieve just a tenth of this value, and thus are no rival to metals for stiffness-critical applications. Fortunately, the difference is not as great with regard to specific strength (derived using the same method: σ / ρ.
There is one final, important nuance. The specific stiffness formula **E/**ρ actually only applies to objects or construction elements subject to a tensile stress (such as a lift cable). For an aircraft wing or a bridge, both of which are "beams" subject to bending stress, the **square root of the stiffness** has to be introduced into the formula, which increases the relative importance of the specific weight. And for constructions which are subject to **compressive stress and easily buckle, or for plates in bending,** the **cubic root** of the stiffness has to be used ($E^{1/3}/\rho$, see green line in Fig. 7), and the importance of the weight increases even more. Because of this, plastics do come considerably closer to metals, but the difference remains substantial. Bridges made entirely of plastic are hard to find.
The two material parameters are represented in Fig. 7 by the blue line (for **E/**ρ) and the green line (for $E^{1/3}/\rho$). It is clear that for both criteria, polymers perform worse than metals. However, composites (being fibre reinforced polymers) outperform even metals. Hence, composites combine the low density of polymers with the high stiffness of the fibres, resulting in stiff and light materials, as shown in Fig. 8.

3 This can be partially explained (in simplified terms) as follows: stiffer bonds draw the atoms closer together and hence lead to heavier metals, while conversely, heavier atoms also usually form stiffer metallic bonds.

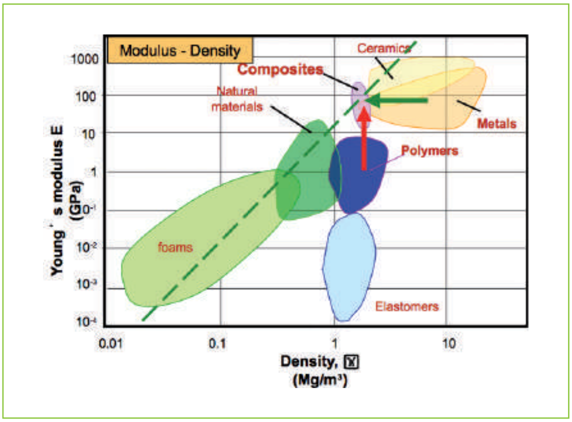


Figure 8: Composite materials combine the stiffness of fibres (similar to the stiffness of metals) with the lightness of polymers (based on M. Ashby et.al., Materials, Butterworth-Heinemann, Oxford, 2007).

5. Natural fibres, another Darwin product

However, you do find that wooden bridges, and flax or hemp fibres have been used for hoisting ropes for ages past. Yet wood and flax fibres are 'natural polymers'. Can nature help us in our search for materials that are simultaneously stiff and light?

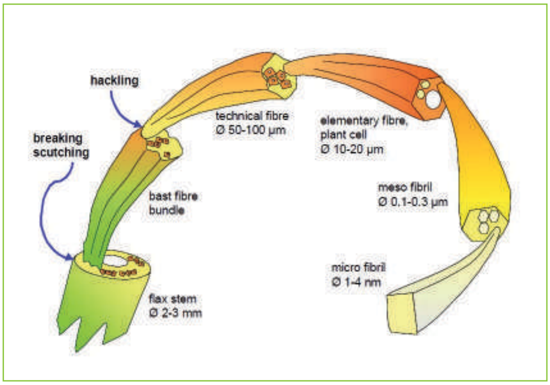


Figure 9: The microstructure of a flax stalk: elementary fibres align parallel with the axis of the plant; inside them, the cellulose crystals are also nicely aligned (source: *Van den Oever*).

On closer examination, the secret lies in the interplay between the two types of bonds in polymers: if you can succeed in orienting all the stiff (primary) bonds in a single direction, the polymer becomes very stiff in that direction (and more flexible in all other directions). Evolution has come up with plants in which the molecular structure is adapted so that they are very stiff in one direction. **Flax stalks need to stay upright in all types of weather, and keep the linseed dry above the ground.** The very slender flax stalk (more then half a metre high and around three millimetres thick – roughly the same height/thickness ratio as a vaulting pole) is therefore constructed from closely aligned cellulose chains, whose stiff primary bonds run almost parallel to the stalk itself, meaning that they are optimally stressed. As a result, **flax has the same stiffness as aluminium, yet is more than twice as light.** The result is a specific stiffness that is twice as great as that of aluminium. An analogous phenomenon is found in all tall, slender plants, such as hemp or bamboo. However, where the need to withstand bending no longer applies, the closely aligned bond structure disappears too: cotton fibres come from the flower rather than the stem, and their job is to protect the seeds. The need for pronounced stiffness disappears, and so too does the pronounced alignment of the cellulose chains. Accordingly, cotton fibres are far less stiff than flax or hemp fibres *(see also Chapter 2 on fibres)*.

Can nature be copied? It was not until the mid-1970s that the first man-made polymers (or 'synthetic materials') with a closely aligned molecular structure were produced. When polyphenylene-terephthalamide, better known under its brand name Kevlar®, is spun in a particular way, fibres oriented in the same way are produced. Fibres are then obtained with a stiffness of up to 140 GPa, nearly twice as stiff as flax or aluminium. A few years later, this was repeated for polyethylene, and new polymer fibres with a high degree of stiffness have been developed since then on a regular basis.
The **spinning process is thus essential in order to obtain the molecular orientation**, and hence the high degree of stiffness. It has only recently been realised that in this respect too, nature got there first: spiders make cobweb using a sort of spinning process, in which they orient the protein molecules in the direction of the fibre with great efficiency.

However, the ultimate in stiffness is found in **carbon fibres.** Like a lead pencil, they consist of graphite, a layered bond structure of carbon atoms. These tiny layers are held together only by weak secondary bonds like the chains in a polymer, but in the layers themselves, there are stiff, two-dimensional bonds present. The more closely these can be oriented in parallel with the fibre axis, the stiffer the carbon fibres. Even an 'ordinary' carbon fibre has a stiffness of 230 GPa (three times greater than aluminium and slightly more than steel), yet only weighs 1.75kg/dm^3.

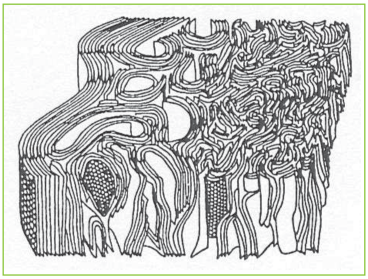


Figure 10: The oriented microstructure of carbon fibres: aligned graphene layers (similar to the aligned cellulose crystalline microfibrils in flax fibres). Fibre axis is vertical.

How do **glass fibres** come into all this? Much more industrial use is made of these than of carbon fibres (the total annual production is twenty times greater), yet their stiffness is a 'mere' 70 GPa, the same as for flax and aluminium... and for ordinary window glass. Thus, spinning glass does not lead to stiffness any greater than that of ordinary cast glass, because the bond structure cannot be aligned. Moreover, glass is fairly heavy (2.55 kg/dm^3, nearly as heavy as aluminium), so that the specific stiffness does not rate highly either. So why are glass fibres so successful? Their secret lies in their great strength, which is determined not so much by the internal structure of glass (which is an intrinsically brittle material), as by the absence of small cracks.

There remains one final, non-negligible reason why glass fibres are used far more than carbon fibres. They are approximately ten times cheaper (€2/kg as opposed to > €20/kg). Here, too, the comparison with traditional construction materials is interesting: the cost of glass fibre is in-between that of synthetic materials and steel (€1 to €3/kg) and that of aluminium (€3 to €5/kg).

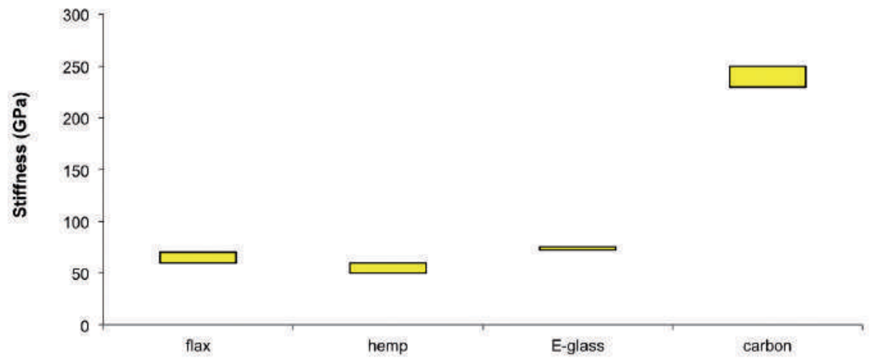


Figure 11: Comparison of stiffness E of natural (flax, hemp) and man-made fibres (glass, carbon).

How do natural fibres, and more specifically **flax** and **hemp**, compare with glass and carbon fibres? In stiffness, they are equal to glass (~70 GPa) and about 1/3 of carbon (Fig. 11), but when the density is taken into account (hence comparing the specific stiffness E/ρ, flax and hemp perform better then glass fibres (Fig. 12). Furthermore, when looking at the specific stiffness in bending $E^{1/3}/\rho$, the values for flax fibres approach those for carbon fibres (Fig. 13)!

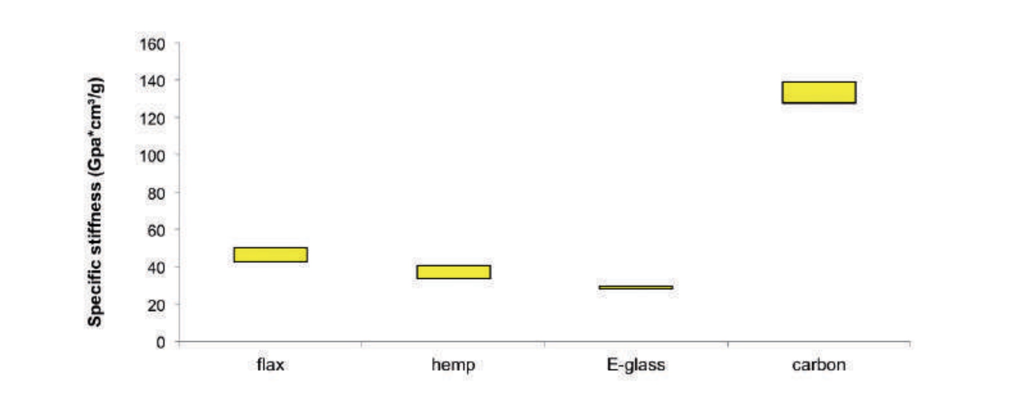


Figure 12: Comparison of specific stiffness E in tension of natural (flax, hemp) and man-made fibres (glass, carbon).

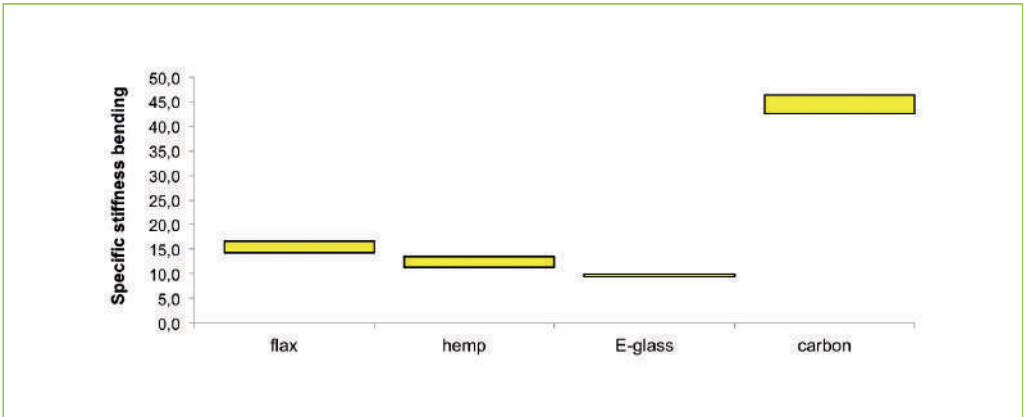


Figure 13: Comparison of specific stiffness in bending $E^{1/3}/\rho$ of natural (flax, hemp) and man-made fibres (glass, carbon).

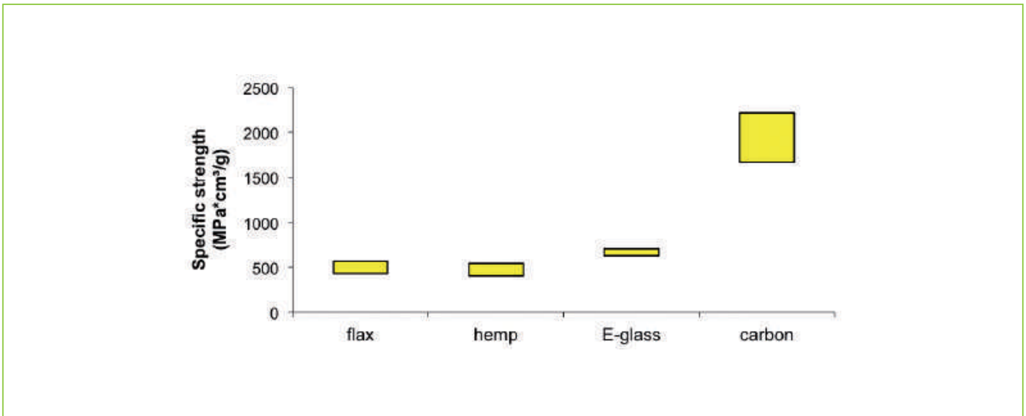


Figure 14: Comparison of specific strength of natural (flax, hemp) and man-made fibres (glass, carbon).

The **strength performance** of flax and hemp fibres is not as good (1/2 that of glass, 1/3 that of carbon fibres), for reasons that will be explained in Chapter 2. However, when you take into account the lower density, the specific properties compare very well with those of glass fibres (Fig. 14).
The final advantage of natural fibres is their much **lower environmental impact** (Fig. 15). Taking the energy needed for producing one kg of fibres as a comparative parameter, flax requires under 10 MJ/kg, or 5 times less than glass fibre, and 25 times less than carbon fibre.

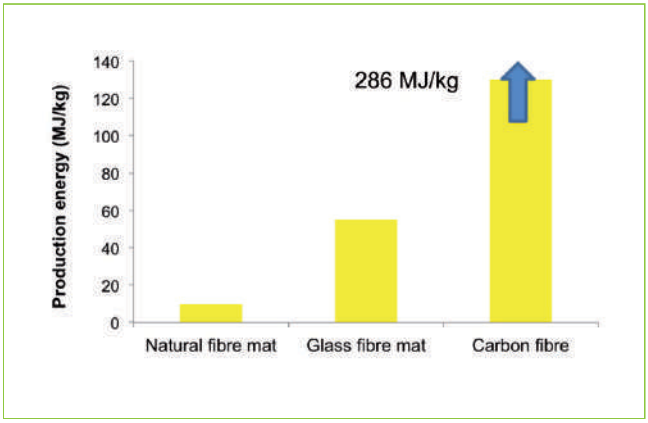


Figure 15: The energy needed for producing 1 kg of flax, glass and carbon fibres.

6. Can I knit an aircraft, or a chair?

Glass, flax, carbon and aramid are all fibres with brilliant specific properties – but can they be used to make an aircraft or a chair?

Figure 16: Knitting a chair: only when the fibres are immobilised by the matrix, a plastic of polymer (campaign image by JEC for Composites-on-Tour exhibition 2006).
Source: *Twintex composite chair-Rhode Island School of Design (RISD).*

In fact, fibres can only be used to make yarns, ropes and cables, and these can only withstand tensile stress. If you push lengthwise on a rope, the fibres separate and the rope loses all its resistance. If you pull sideways on a rope, the fibres fray.
Yarns can be connected together to make woven fabrics, knitted fabrics or braided fabrics. Such textiles only feel stiff if they are subjected to a stress in the fibre direction. If you pull on the corners of a handkerchief, you will experience far less resistance than if you pull in the fibre direction of this piece of woven fabric. This is because in a diagonal direction, the fibres can slide over one another. The force is not transmitted to the fibres.

If one really wishes to exploit the intrinsic stiffness of fibres for building (semi-) structural products, one must ensure that the fibres cannot move relative to one another when a force is applied. An engineer would say that one has to ensure that the forces are transmitted to the fibres, without the fibres being able to move freely. A comparison can be made with taking in frozen linen from the washing line in the garden on an icy-cold winter's day. The usually flexible tea-towels and T-shirts have suddenly turned into hard, non-deformable 'structures'. Of course this is partly because of the layer of ice, but without the flax in the linen tea-towel or the cotton in the T-shirt, these deep-frozen items of clothing would not feel nearly as stiff. The frozen water causes the fibres to become immobilised, meaning that the forces can be efficiently transmitted to the fibres. And because flax and cotton fibres are intrinsically stiffer than ice, a frozen T-shirt feels very stiff.

7. The composite concept

The secret behind high stiffness and strength of composites has thus been discovered! If the fibres can be immobilised, and actually made to adhere to one another, the outstanding stiffness of flax and carbon fibres and strength of glass fibres can be exploited. If a light material is used for such a 'glue', the 'combined' material, or the composite, will also remain light. Plastics may be flexible and not particularly strong, but they are just strong enough to fulfil the function of immobiliser.
Stiff fibres in a flexible plastic: does this result in a stiff or a flexible composite? Is it like mixing colours? Black paint mixed with white gives a grey colour. The more black is added, the darker the grey. Is this also the case with fibres in a synthetic matrix?[4] The answer to this question is neither unambiguous nor simple. Some properties follow this rule, while others do not at all.

Intuitively one feels that mixing a heavier material with a lighter one will produce a 'composite' whose (specific) weight lies somewhere between the two. If you mix one kilogram of glass fibres (2.55 kg/dm^3) with one kilogram of polyester (1.25 kg/dm^3), the specific weight of the composite will lie right in the middle (1.9 kg/dm^3); if the mix ratio is one-quarter glass fibres to three-quarters polyester, the specific weight of the glass fibres only counts for one-quarter, while that of polyester counts for three-quarters (result: 1.5 kg/dm^3). This kind of **simple mixing rule is called 'linear' (Fig. 17),** or one can say that the composite property is proportionate to the proportions of the two components *(more extensive explanations on mixing rules to predict composite properties will be discussed in Chapter 7).*

4 'Matrix' is used as a general term to designate the material that causes the fibres to adhere to one another. Metal matrix and ceramic matrix composites also exist.

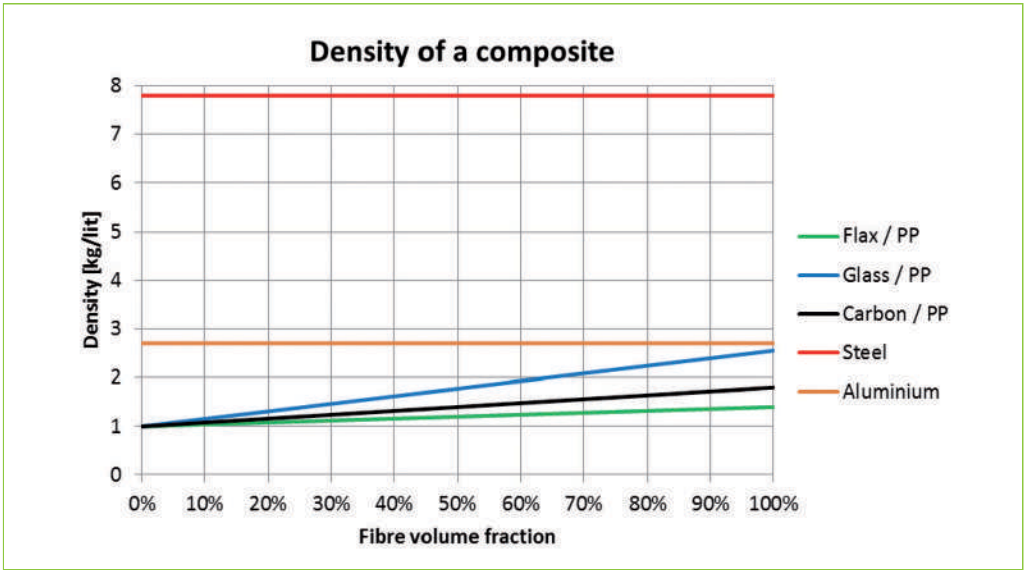


Figure 17: Simple linear rule of mixtures for the density ρ of a composite, applied to flax (ρ = 1.4 kg/lit), carbon (ρ= 1.8 kg/lit), and glass fibres (ρ= 2.55 kg/lit), in a polymer matrix (PP, ρ= 1.0 kg/lit). ***Values for steel and aluminium are added as horizontal line for reference.***

Expressed as a formula:

$K = \alpha_v . K_v + \alpha_m . K_m$,

where K is the **property**, α_v is the **fibre volume fraction** and α_m is the **matrix volume fraction.** For natural fibres, the effect is less important, because they are only slightly heavier than polymers (typically 1.4 kg/dm^3). However, for carbon and glass fibres, the density strongly increases with increasing fibre volume fraction.

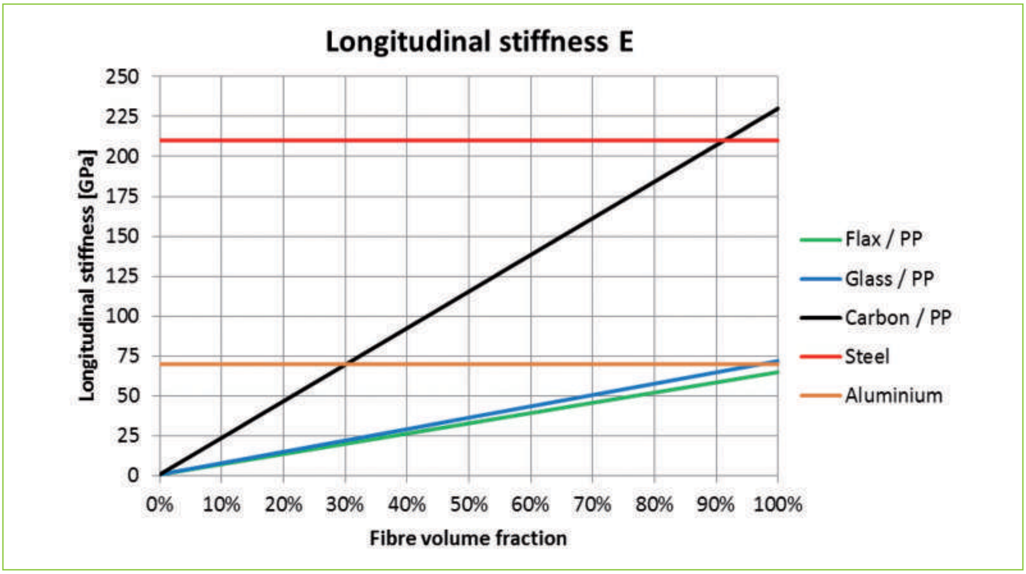


Figure 18: Simple linear rule of mixtures for the longitudinal stiffness E of a composite, applied to flax (E= 65 GPa, carbon (E= 230 GPa), and glass fibres (E= 70 GPa), in a polymer matrix (PP, E= 1 GPa). ***Values for steel and aluminium are added as horizontal lines for reference.***

For the mechanical properties, stiffness and strength, the picture is more complex. In a very simple composite, in which all the fibres lay nicely parallel to one another (a **'unidirectional'** composite) the **longitudinal** or lengthwise **stiffness** (the stiffness and strength in the fibre direction, i.e. in the direction of pull on this rod) follows the same, simple linear mixing rule as for the density ($K = \alpha_v . K_v + \alpha_m . K_m$).
An **equal quantity (by volume)** of flax fibres (stiffness: 65 GPa) and polypropylene matrix (stiffness: only 1 GPa) produces a stiffness that lies right in the middle (33 GPa). Compared with the flax fibres, this represents a reduction by nearly half, but compared with the polypropylene matrix, the stiffness has been increased 33 times (Fig. 18)! Moreover, the specific weight increases only slightly, from 1.0 to 1.2, so that the specific stiffness E/ρ (Fig. 19) is higher than metals (steel, aluminium: approximately 25), as soon as the flax fibre volume fraction exceeds 50%.

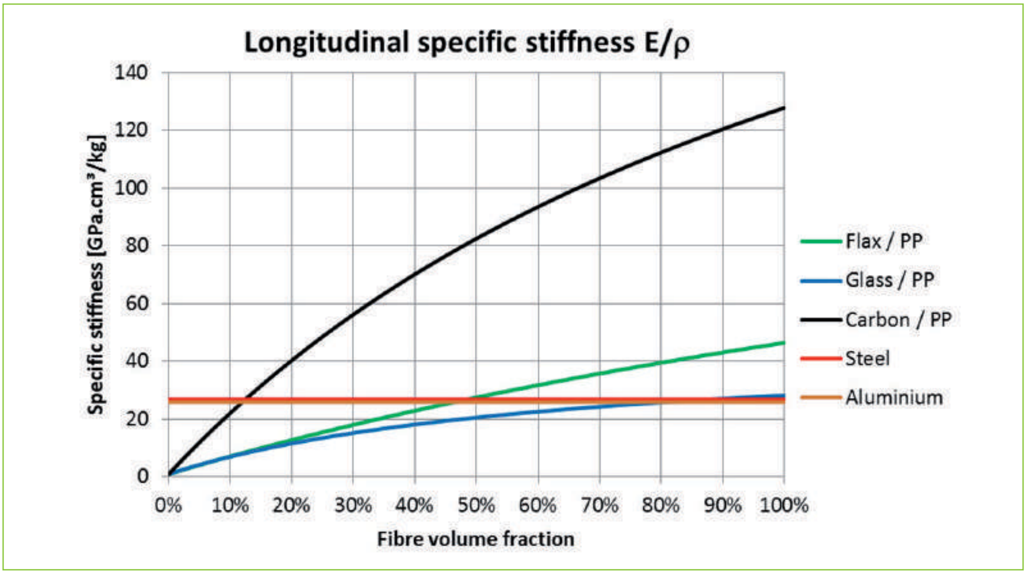


Figure 19: The rule of mixtures gets somewhat more complex for the longitudinal specific stiffness E/ρ of a composite, applied to flax, carbon and glass fibres, in a polymer matrix. Values for steel and aluminium are added as horizontals line for reference.

For the cables of a suspension bridge (loaded only in tension), carbon fibre composites would be the lightest solution (E/ρ = 110), followed by flax composites (E/ρ = 27), steel or aluminium (E/ρ = 25) and glass fibre composites (E/ρ = 20). In principle, this order of precedence also applies to the wings of an aircraft, but as they are loaded in bending, the specific stiffness in bending $E^{1/3}/\rho$ is used (Fig. 20). The superior properties of carbon fibre composites become even more pronounced, but flax composites also nicely outperform glass fibre composites.
It is therefore not surprising that the new jumbo from Airbus (A380) is one-quarter produced from carbon fibre composites, twice as much as earlier models. This has set a trend: the very latest models from Boeing (787) and Airbus (A350) are constructed by as much as 50% from carbon fibre composites. Nor is it any wonder that hardly any glass fibre composites are used in aircraft. They are simply not stiff enough. But can no use be made of the outstanding strength of glass fibres?

The first question to ask is whether the **strength in the fibre direction** follows the same simple mixing rule as the stiffness. For most fibre-reinforced synthetic materials, this is indeed the case. A unidirectional composite that comprises 50% by volume of strong glass fibres (strength 1500 MPa) and 50% of a weak synthetic material (100 MPa), has a strength that lies right in the middle: 800 Mpa, which is eight times stronger than the matrix and around twice as strong as a good aluminium alloy, for a much lower specific weight.

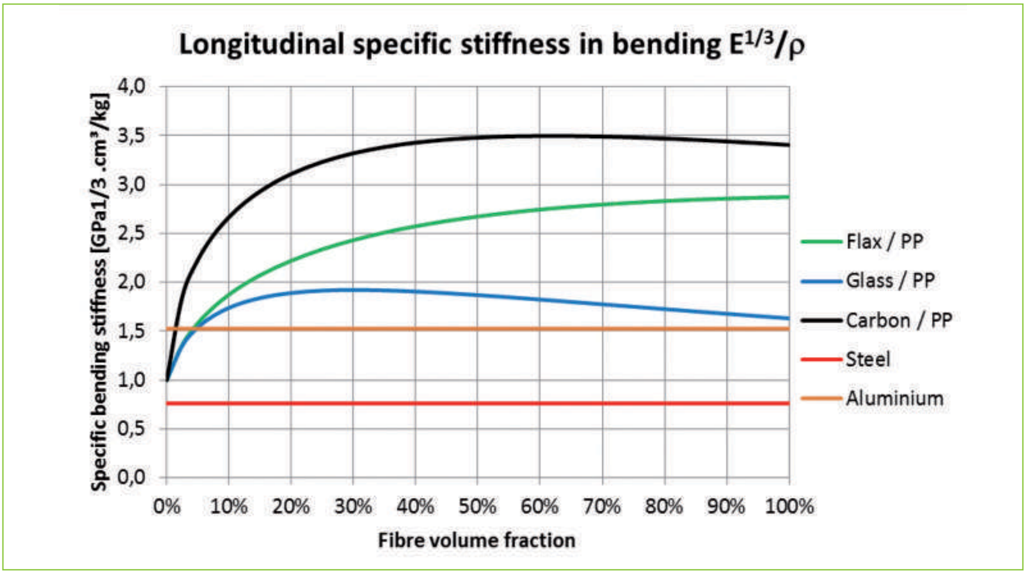


Figure 20: The rule of mixtures gets even more complex for the longitudinal specific stiffness in bending $E^{1/3}/\rho$ of a composite, applied to flax, carbon and glass fibres, in a polymer matrix. ***Values for steel and aluminium are added as horizontal lines for reference.***

8. The orientation effect

The composite effect – the drastic increase in stiffness and strength that results from the addition of fibres to a synthetic material – is very clear in an idealised composite (in which all the fibres lay neatly in parallel with one another), and only when the force is applied parallel to the fibres. But what if this force has a different orientation? Do you get an effect similar to that found with wood? If you bend a thin plank of wood perpendicular to the direction of the grain, it feels far more flexible than if the bending force is applied in the direction of growth (the 'anisotropy' effect).

The same phenomenon is found in composites, and to a far greater extent. The stiffness under a stress which is perpendicular to the fibres, also known as the **'transversal' stiffness,** is far less than the longitudinal stiffness. It is determined by another mixing rule expressed as a formula:

$1/K = \alpha_v/K_v + \alpha_m/K_m$

(The formula above represents a "lower bound"; more precise formulas predict slightly higher transverse stiffness values, like Chamis' formulas).

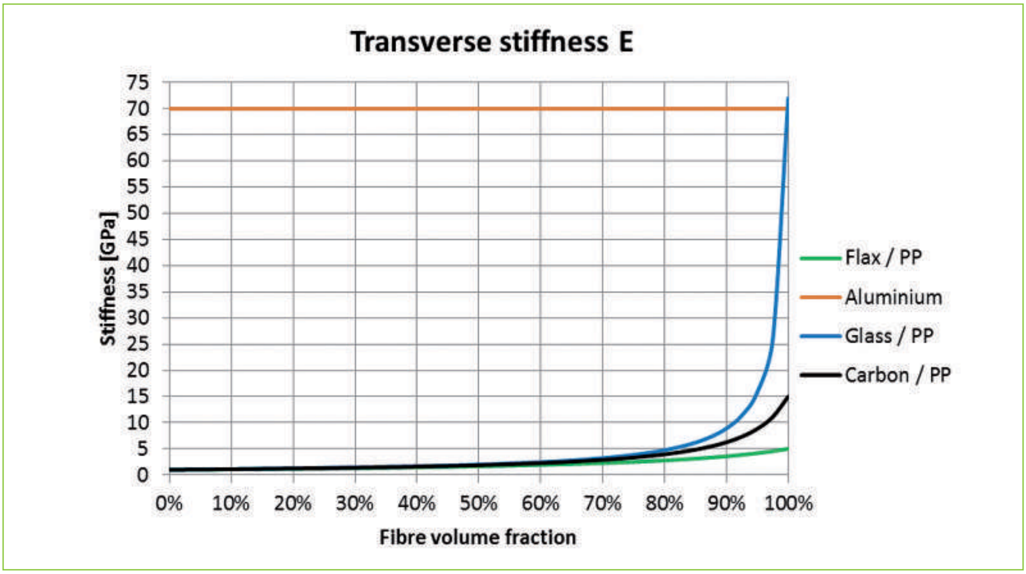


Figure 21: The non-linear rule of mixtures for the transverse stiffness E (using Chamis' formula) of a composite, applied to flax (E= 5 GPa), carbon (E= 15 GPa), and glass fibres (E= 70 GPa), in a polymer matrix (PP, E= 1 GPa). ***Values for steel and aluminium are added as horizontal lines for reference.***

In Figure 21, we can observe that, up to quite a high fibre percentage, the transversal stiffness remains close to the low stiffness of the plastic matrix. A 50/50 (by volume) composite with glass fibres has a transversal stiffness of just 6 GPa, compared with a longitudinal stiffness of 36. In carbon fibre composites, the difference is even greater, but also in flax and hemp fibre composites. The reason is that the radial (or transverse) stiffness of these fibres themselves is much lower than their longitudinal stiffness (15 vs. 230 GPa for carbon fibres, 70 vs. ~5 GPa for flax fibres). Hence, the transverse composite stiffness builds up only very slowly when increasing the fibre volume fraction. Glass fibres, however, are isotropic (70 GPa in longitudinal and radial direction), and the transverse composite stiffness increases faster.
Unidirectional composites are hence always **very anisotropic, as shown in Fig. 22.**

How is a designer supposed to cope with this? He or she will be accustomed to working with steel, aluminium or plastics, which do not display such a confusing variation in properties. Regardless of the direction in which you bend a metal or plastic sheet, it will always have the same resistance (these are **'isotropic'** materials). This simplifies both the design work and the production process considerably.
With composites, however, the designer needs to take into account the **anisotropy**, determined by the fibre orientation, as shown in Fig. 23.

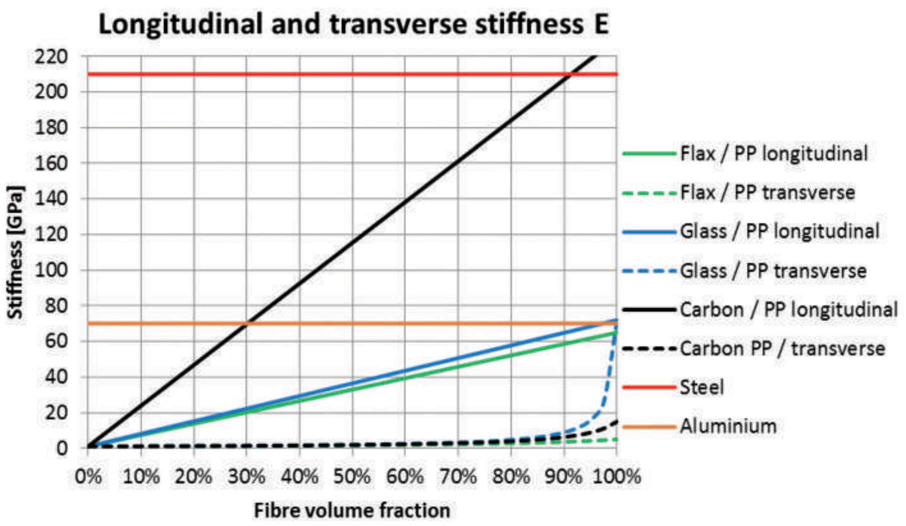


Figure 22: Anisotropy in composites: the difference between longitudinal and transverse stiffness E of a composite, with flax, carbon and glass fibres in a PP polymer matrix. ***Values for steel and aluminium are added as horizontal lines for reference.***

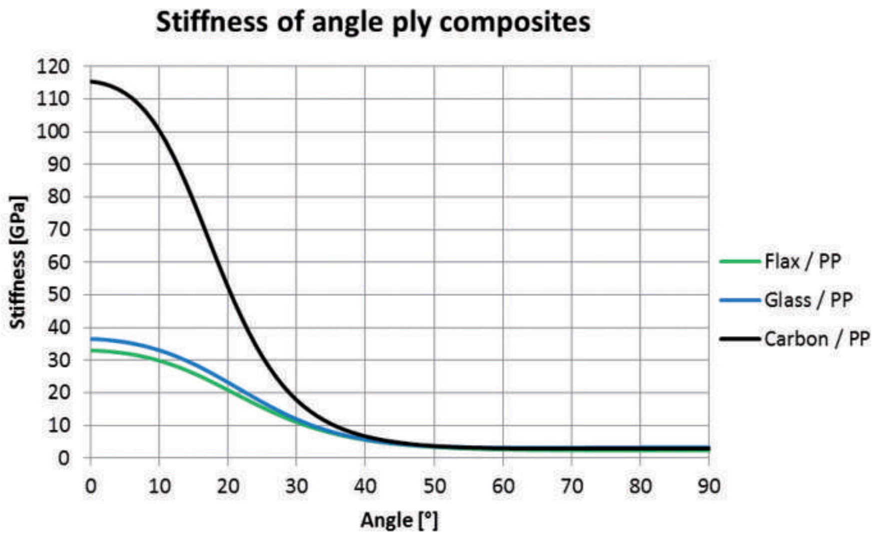


Figure 23: Variation of the stiffness of an "angle ply" composite (fibres in +/- γ– direction), with flax, carbon and glass fibres (50% by volume) in a PP polymer matrix.

Naturally, a designer has more choice than just these two extremes: the high longitudinal and the low transversal composite properties. He or she can play with the fibre orientation and hence match the properties in specific directions with the expected stress in that direction. This is a unique advantage of composites: the designer does not just create the product's form, but can also create an optimal material for that form. As he or she works with these new materials, the designer is invited to conceive new materials.

This occurs with highly technical designs, such as an aircraft wing, which is constructed from dozens of wafer-thin layers of unidirectional carbon fibre composite, each of which is individually and completely anisotropic (eighty times stiffer in the fibre direction than in the perpendicular direction). But by giving each layer a different direction relative to the wing's longitudinal axis, one can find the right mix for the complex stress to which the wing is subjected, meaning that the wing's weight can be really minimised. A material of this kind which is built up in layers is known as a laminate.

9. Textile: an old technology for advanced materials

However, a composite is not always constructed from thin, unidirectional layers with varying orientations. Since time immemorial, fibres have been combined into yarns and then woven, braided or knitted together. In a **woven** fabric, warp and weft yarns form a 90° angle to another; although triaxial woven fabrics also exist, these are rather exceptional. In a **braided** fabric, a longitudinal yarn can be 'threaded' between the two braided yarns, so that a material is obtained with three fibre orientations (0° and $+/- \gamma$). In a **knitted** fabric, finally, the loop structure in each fabric layer ensures a continuously varying fibre orientation.

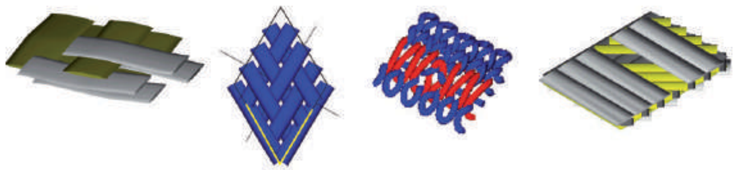


Figure 24: Basic textile types used as composite reinforcement: woven, braided, knitted and non-crimp fabrics (from left to right).

Thus far, knitted fabrics have been used the least. This is because it is not very easy to make small loops out of relatively brittle glass or carbon yarns. However, knitting technology has led to a new type of textile, which is virtually unused outside the world of composites: **non-crimp fabrics.** These represent a return to the unidirectional glass or carbon fibre layers, which are now knitted together by means of very fine threads (usually made of polyester). This produces a multi-layered semi-finished product, in which the unidirectional layers are already fixed in the fibre orientation that they will later need to assume in the composite.

Textile technology has thus helped composite designers and producers to achieve varying fibre orientations in an economical fashion. But it has to be remembered that greatly varying mechanical properties are obtained in the process, lying somewhere between the high longitudinal and low transversal properties.

How do you make it?
Further on in this book (Chapter 6), it will be explained how composite products and structures are being produced and which polymers are being used for this.

10. Some economical aspects

Worldwide, the volume of the composites market is 8 million tons, 25% of which is being produced in Europe (source: JEC, Rouen, June 2011).
At an average price of €7.2/kg, this represents an annual turnover of €60 billion! In volume, the applications in transportation take the largest share (28% globally, 33% in Europe), followed by building and construction (27% globally, with only 21% in Europe), and electrical & electronics (16%). Whereas the share of wind energy applications is globally still small (only 3%), in Europe it has already reached 7% and is steadily growing.

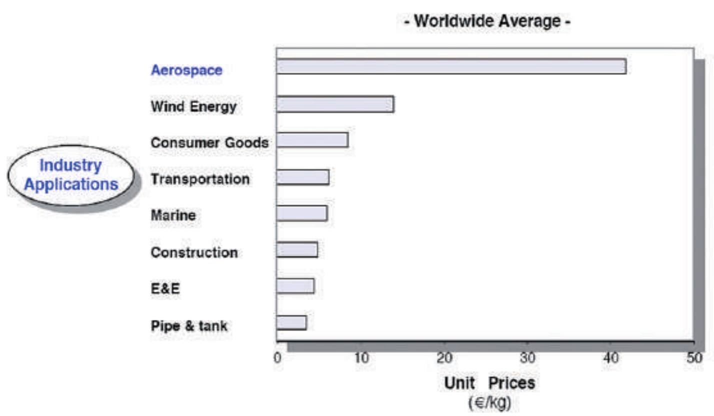


Figure 25: Average price of composite materials used in different application areas. (source: *JEC presentation at JEC-Forum 2011*)

It is remarkable that the cost per kilogram of a composite material varies widely as a function of the application area: composites for aerospace applications cost on average just above €40/kg, almost three times more than for windmill applications, and four times more than for consumer goods (see Fig. 25).

Finally, there is an interesting correlation between the composites consumption per inhabitant and GDP (Fig. 26): a steep increase in the consumption can be observed once a certain level of GDP is reached. This offers very interesting perspectives for consumption of composites in the more recently developed economies of the BRIC countries (Brazil, Russia, India and China).

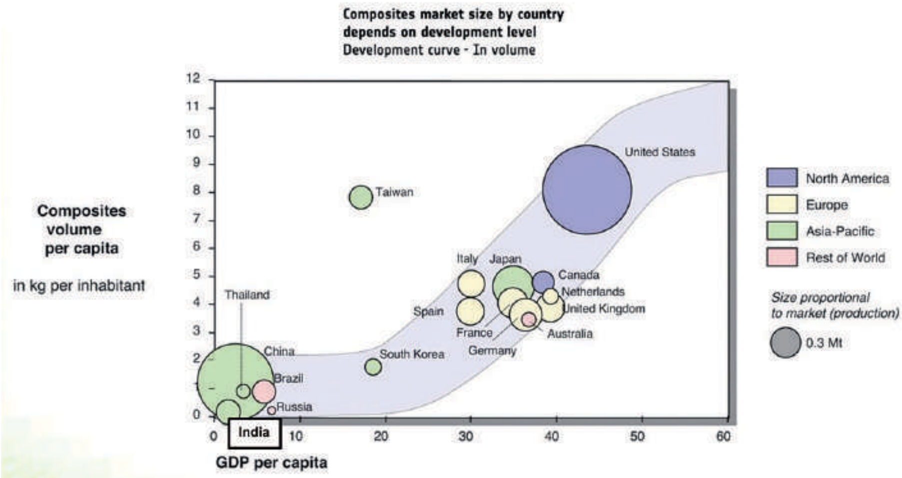


Figure 26: Composites consumption per capita increases with GDP (gross domestic product) per capita (source: *JEC, presentation at JEC-Forum 2011*).

The **share of natural fibre based composites** (excluding wood fibres) in the global composites market is still small. However, it will grow from 20,000 tons (t) in 2010 to 40,000-50,000 t by 2015, according to a report in the latest issue of Technical Textile Markets – a quarterly publication from the global business information company Textiles Intelligence. In another study, presented by Lucintel at the BioForum JEC 2011, the natural fiber composite market (including wood fibres[5]) is expected to reach $ 3.8 B by 2016, representing an average annual growth rate of 10%.

From another perspective, the natural fibres represent 40% of worldwide fibre production (80 million tons, the majority being synthetic fibres). *(Data presented by Gērard Mougin at the JEC-BioForum, 2011).*

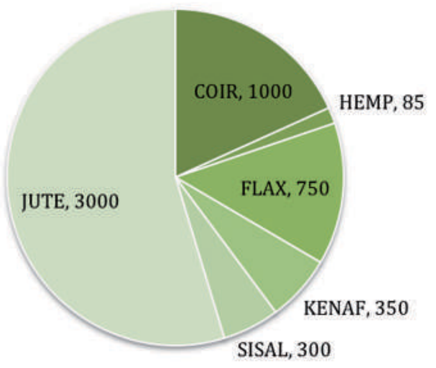


Figure 27: World consumption in kilotons, excluding cotton and wood fibres (source: *Gērard Mougin at the Colloque AFT – FRD, 2011*).

Cotton fibres, the most abundantly produced natural fibres, are not really used in composites. Amongst the natural fibres also used as reinforcement for composites, however, jute leads, followed by coconut fibres and flax. Hemp accounts for only about one-tenth the amount of flax used.

Looking at the use of flax and hemp fibres, one observes that flax fibres are used mainly in textile applications (83%), whereas hemp fibres are used mainly in paper manufacturing. The second most frequent use for both fibres is in composites, with 6% for flax and 10% for hemp.

5 Wood fibres have a much larger share than "plant fibres", as they are used massively in consumer products like extruded deck panels.

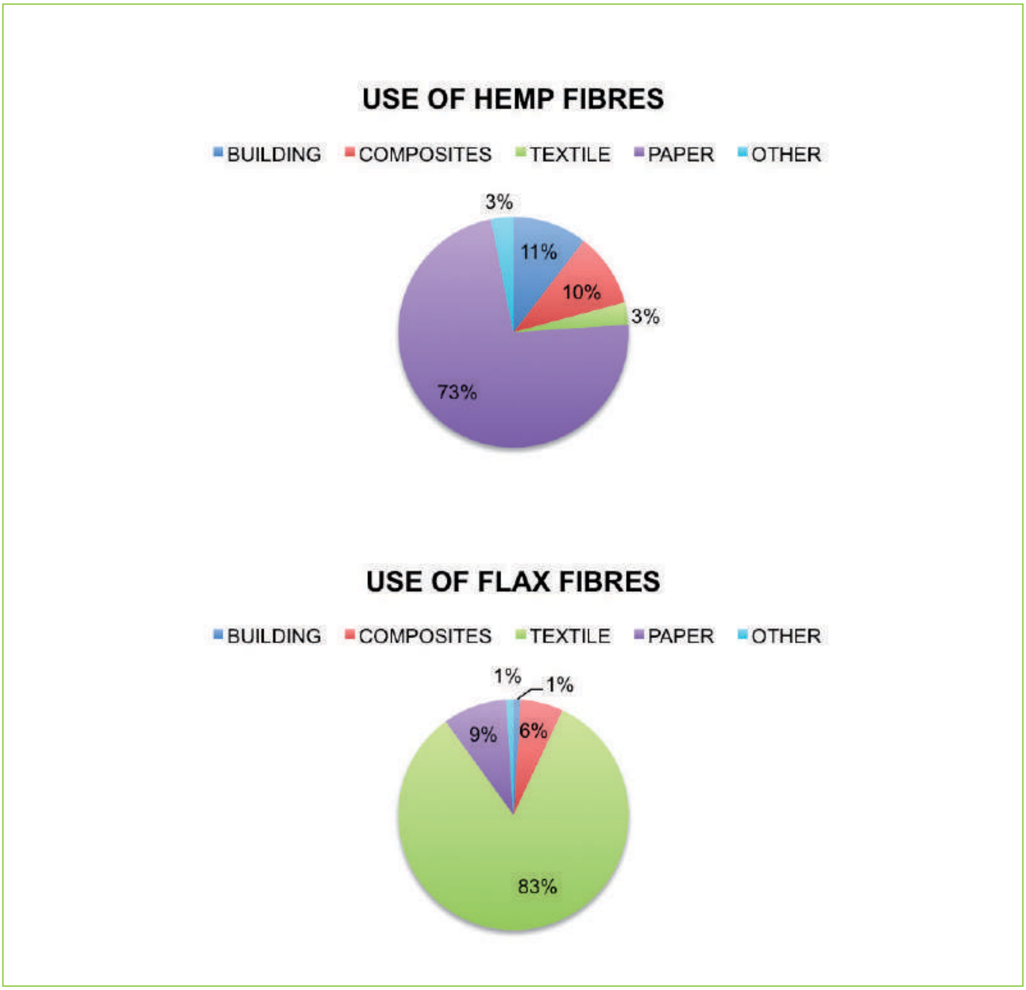


Figure 28: Use of flax and hemp fibres in different application areas (source: *Gērard Mougin, Colloque AFT – F.R.D., 2011*).

The growth potential of natural fibre composites is greater than for composites in general: double-digit growth is expected over the coming five years, and this growth will be even greater in Europe than worldwide (+ 25% compared to +15%/year for 2005-2010).

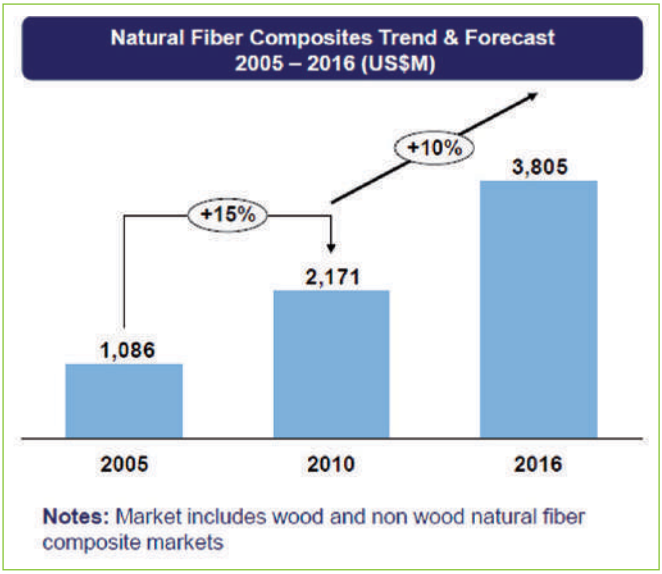


Figure 29: Worldwide growth potential for natural fibre composites (see details in Lucintel study presented at *JEC-Bio Forum, 2011*).

This future growth can be easily realised, as far as flax and hemp fibres are concerned, by re-orienting textile production and increasing the agricultural area used, along with other measures that will be explained in Chapter 10.

- II - Reinforcements: fibres

Jörg Müssig,
Professor at University of Applied
Sciences, Bremen, Germany (HSB)

Mark Hughes,
Professor at Aalto University,
Espoo, Finland

1. Introduction

In order to use natural fibres successfully in composite applications, it is first important to appreciate the wide variety of natural fibres available and their properties. This is the main aim of this chapter. The type of fibre, its morphology, structure and chemistry will all play a part in determining the final fibre properties and characteristics. Other factors come into play too. How the fibres are processed and the presence of naturally occurring features as well as process induced damage, for instance, will to some extent all affect the properties of the fibres and, ultimately, the properties of the final composite too.

2. Types of fibres

A great number of fibres can be found in nature. Figure 1 provides an overview of some of the more important 'natural fibres'.

The first main difference to be seen is that the term 'natural fibre' includes both organic and inorganic fibre. Both can be, and have been, used as composite reinforcement; however this chapter is only concerned with the most industrially significant organic plant fibres - cotton, flax, hemp, jute, ramie, coir, abacā and sisal, with particular focus on flax and hemp.

3. Arrangements in plants

There is an enormous variety of plant fibres, and their properties and morphology depend upon both the location of the fibres in the plant and their function. As may be seen from Figure 2, plant fibres are found in different positions in the stems of monocotyledonous (plants with one cotyledon; abbreviated to monocot) and dicotyledonous (plants with two embryonic leaves; abbreviated to dicot) plants as well as dicotyledonous and gymnosperm trees. Other technical plant fibres are the so-called mesocarp fibres of which coir, from the plant *Cocos nucifera* L., is an example. However, the most industrially important plant fibre is cotton. The cotton fibre is a seed hair which, from a botanical classification point of view, is not really a fibre but a trichome. [3]

Of particular importance as composite reinforcement are the so-called bast fibres such as flax, hemp, jute and ramie. These fibres are to be found in the outer portion, the bark, of dicotyledonous plants and are of special interest because of their excellent stiffness and strength properties. Flax and hemp plants have been cultivated in Europe for centuries for their

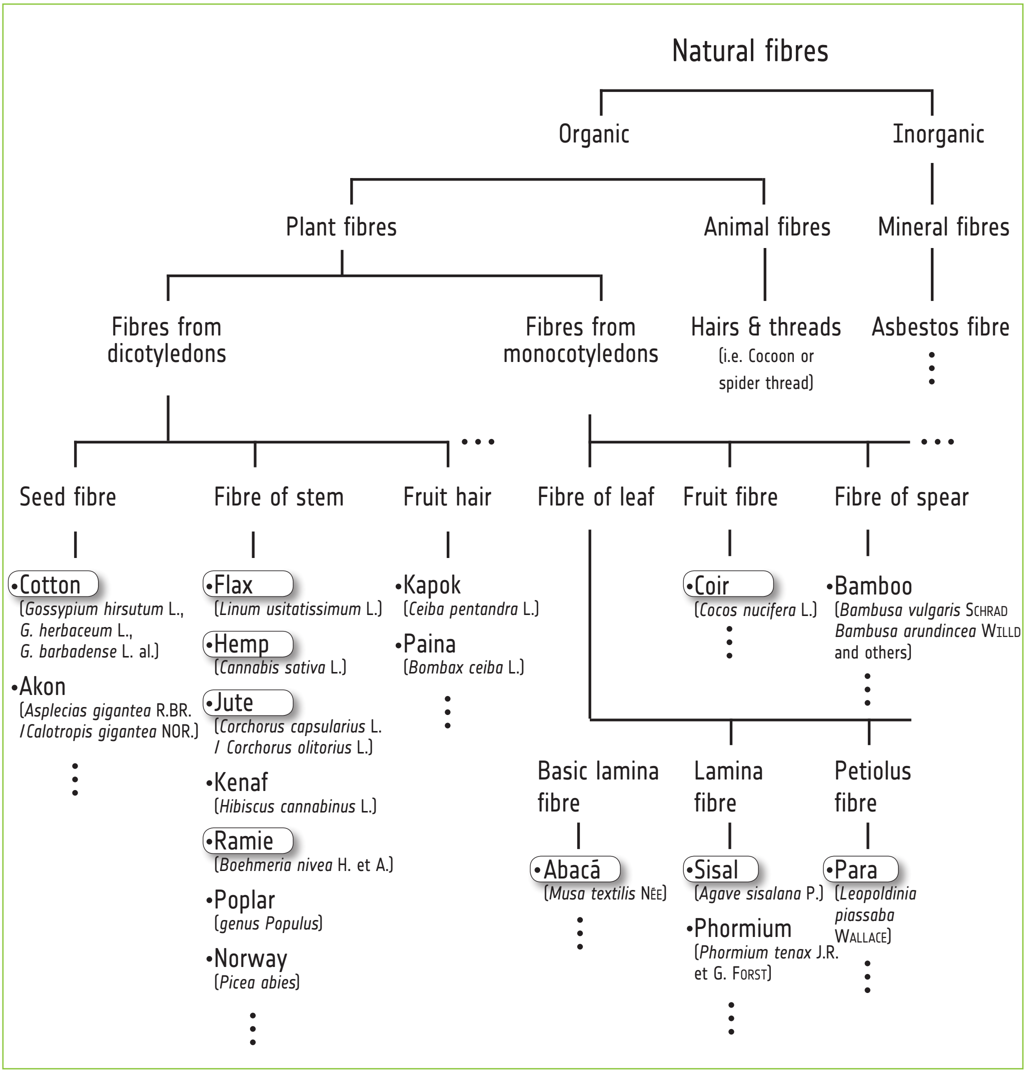


Figure 1: Overview of natural fibres ([1] – adapted and expanded from [2]). Further information about selected fibres (encircled) will be found in this chapter.

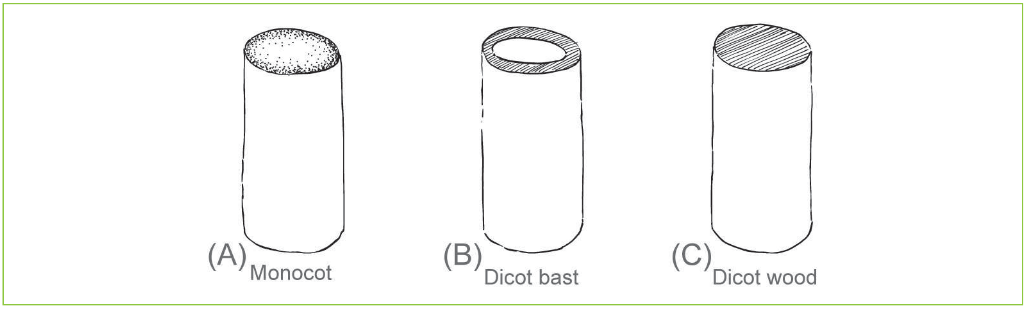


Figure 2: Schematic representation of the possible locations of fibres within stems of monocotyledonous and dicotyledonous plants and trees (both dicotyledonous and gymnosperm trees) (adapted from [3]).

fibres, which have been used in technical applications such as canvas and cordage. An overview of the traditional flax value-added chain is given in Figure 3.

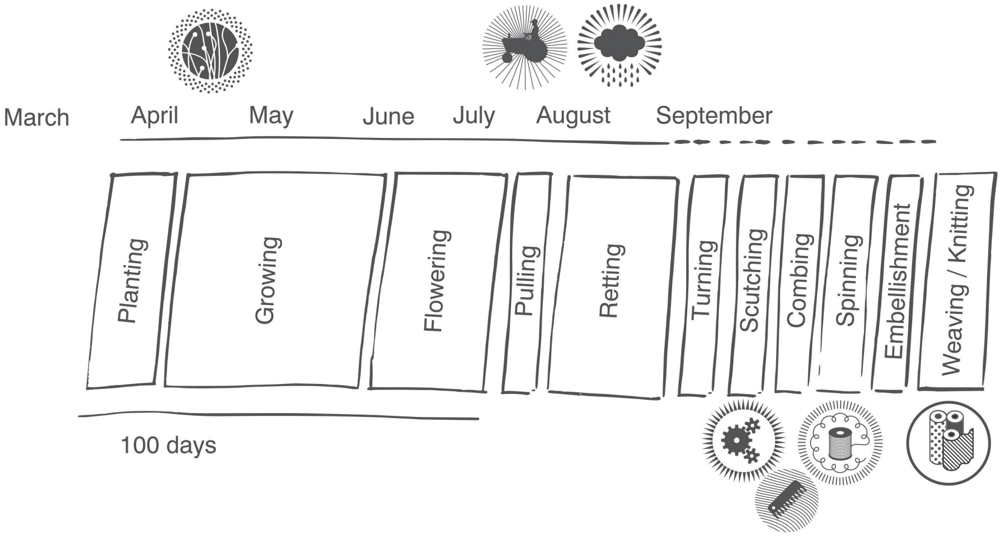


Figure 3: The traditional value-added chain from flax plant to textile products.

The typical appearance of flax and hemp plants can be seen in Figure 4. Flax (*Linum usitatissimum* L.) is an annual plant growing to heights of between 0.7 and 1.2 m, with a thin stem of between 1 and 3 mm in thickness. When grown under standard agricultural conditions in Europe, the stem of the hemp plant (*Cannabis sativa* L.) is, 1.5 to 3.5 m high and has a stem 5 to 20 mm thick.

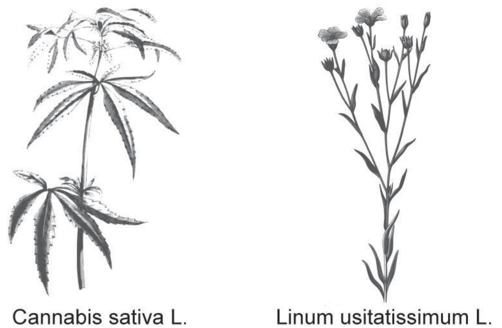


**Figure 4: Left: Hemp (*Cannabis sativa* L.) adapted from [4];
right: Flax (*Linum usitatissimum* L.), adapted from [5].**

4. Chemistry of plant Fibres

Plant fibres consist of strong, stiff cellulose molecules embedded in a matrix of lignin along with a range of polysaccharides, including hemicelluloses and pectins, which are associated with the cellulose and lignin. There are also a number of other compounds including waxes, inorganic salts and nitrogenous substances present in the cell wall, that do not have a structural function. Cellulose itself is a high-molecular-weight, long-chain molecule consisting of β - D anhydroglucopyranose units, bonded with β - (1 → 4) glycosidic linkages. [6, 7 & 8] The axial Young's modulus of cellulose has been reported to be in the region of 135 GPa [9] and as such can be thought of as the ultimate reinforcing agent in plant fibres. In the cell wall of the plant fibre, cellulose exists mainly in the form of highly ordered cellulose molecules embedded in a matrix of other polysaccharides and lignin. These structures are known as microfibrils. The nano-sized, composite-like microfibrils form the cell wall which, in turn, builds the structure of the fibre and ultimately the plant (see Figure 5).

- Table 1 -
Chemical composition of selected natural fibres. Since there is considerable natural variation in these values, the data shown represents typical values most frequently published (values taken from [10])

Substances in %	Flax	Hemp	Jute	Ramie	Sisal	Abacā	Coir	Cotton
Cellulose	70	70	65	72	66	60	40	90
Hemi-cellulose	17	16	15	14	12	21	0.2	4
Lignin	2.5	6	10	0.7	10	10	43	0.7
Pectin	2	1	1.5	2	2	0.8	3	4
Fat/wax	1.5	0.7	0.5	0.3	1	1.4		0.6
Ash	1.5	1.5	0.4	0.3	0.3			1.4
Water solubles	6	1	1	6	3.5	1.4	4.5	0.7

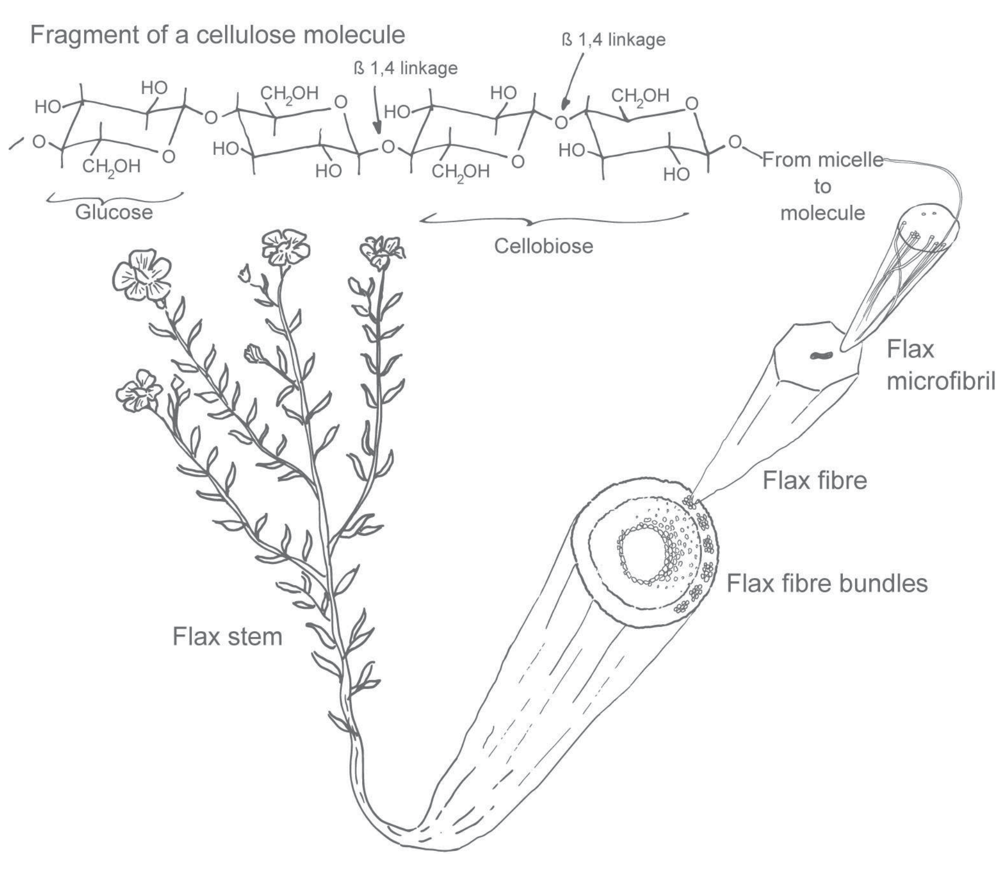


Figure 5: Schematic representation of the hierarchical structure of flax (*Linum usitatissimum* L.) – from plant to cellulose.

5. Decortication & Separation

The process of separating the fibre or fibre bundles from the stems of flax or hemp generally starts in the field. During harvesting, the stems are pulled (typical for flax) or cut (common for hemp) and spread on the ground. Flax and hemp then traditionally undergo a process known as retting to loosen and separate the bast fibre bundles from the remaining stem tissue. During retting, microorganisms, in particular fungi, colonise the stem and the enzymes secreted by these organisms degrade the pectins that are largely responsible for binding the bast fibres to the stem tissue. Until fairly recent times, water retting, which is carried out in rivers or ponds and yields high quality fibre, was practised in Europe; however, the practice has been largely discontinued due to pollution problems.

After the retting process is complete, the stems are collected and transported to the decortication and separation facilities. In the decortication process the woody core material of the stem, known as the ‘shive’, is broken away and mechanically separated from the fibre bundles. Further separation processes may be carried out to refine the fibre bundles further. As may be seen from Figure 6, there are different possible separation processes. Currently, only

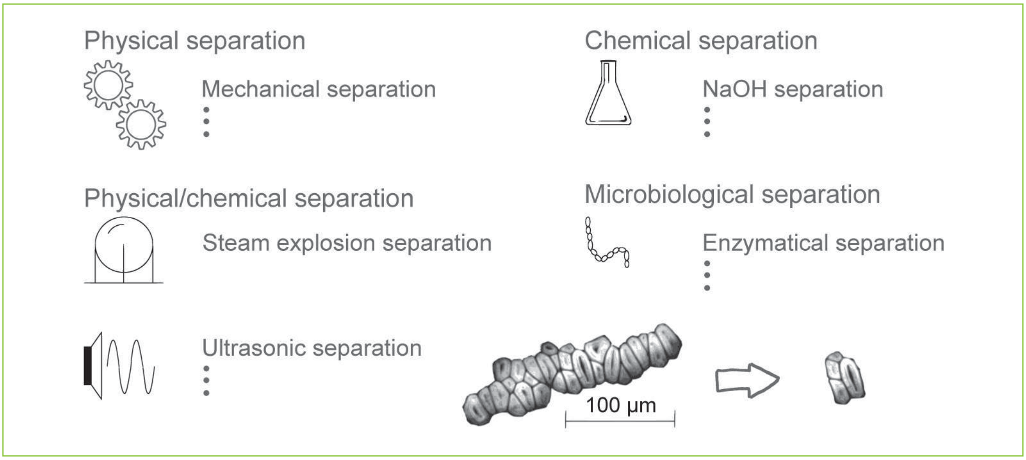


Figure 6: Separation techniques to separate and refine fibre bundles from flax or hemp (adapted from [1]).

the mechanical separation and, to some extent, the chemical and physical/chemical separation processes are used industrially. Enzymatic separation is currently in a transition state from research to commercial reality. [11]

Figure 7 provides an overview of the traditional processing of flax to produce various flax fibre products. Processing of long flax, begins with dew or water retted flax being scutched to break the shive and fibre apart. This is then followed by hackling where the fibre bundles are further cleaned to remove any remaining shive. The orientation of the stems and the fibre bundles is maintained during the entire process from harvest to the final product so as to prevent entanglement and to facilitate easier spinning. In modern flax processing lines, however, the orientation is not controlled in the same manner, resulting in the fibres being more-or-less randomly oriented. The following definitions help to distinguish between the processing techniques: (i) *longitudinal flax*, in which the fibre bundles are oriented in only one direction, and (ii) *disordered flax*, in which the fibre bundles has no preferred orientation. [27]

For hemp processing the situation, especially in Europe, is different to that of flax. Decortication and separation are normally carried out in industrial facilities following two main processing routes. Long hemp (*longitudinal hemp*) for textile applications can be obtained in processing lines that always keep the fibre bundles aligned (in the same way as the flax fibres described above), avoiding tangle which would dramatically reduce fibre yield during hackling. For this purpose, traditional hemp processing lines are still available in Eastern Europe that can scutch hemp stems and hackle the fibre, resulting in long fibre bundles, about the same length as the harvested stem. Alternatively, flax scutching and hackling lines can be used to process short hemp crops, provided the length of the hemp (or flax) stems are around 1 m. The processing of *disordered hemp* (fibres and fibre bundles have no preferred orientation) is in reality far more common in hemp processing across Europe and various lines have been developed for the purpose. [13]

After harvesting the hemp, the stems are usually, but not always, retted, after which they will be baled in the field and transported to the decortication and separation facility. In the processing of *disordered hemp*, the parallel orientation of the stems or the fibre bundles will not be maintained. Different bale opening, decortication and separation techniques have been developed for *disordered hemp* and Figure 8 illustrates alternative solutions that are used for the four main steps involved in the processing of baled hemp stems.

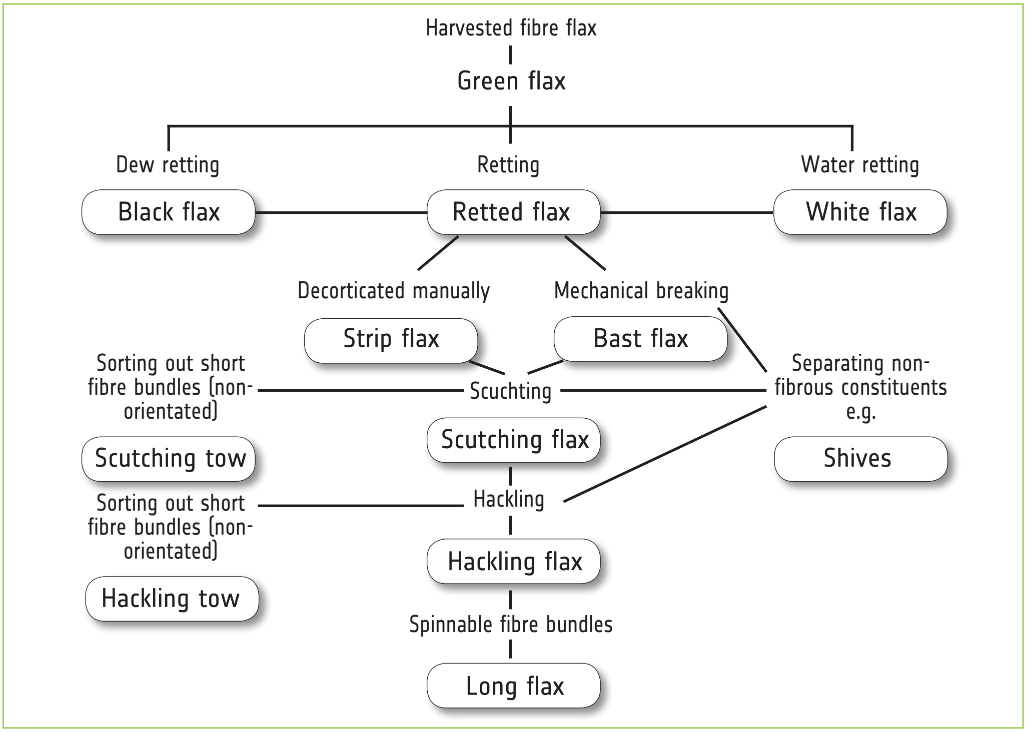


Figure 7: A schematic overview of the systematic nomenclature used in traditional flax processing products. From [12] adapted to flax [2].

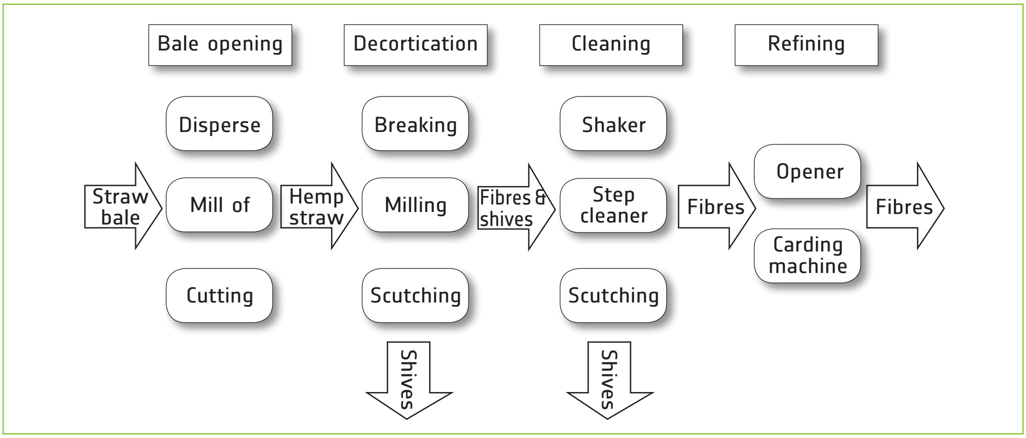


Figure 8: Main steps in industrial hemp processing; the arrows show the process flow and the resulting product; the rectangles at the top are the different steps in the processing; the rounded rectangles symbolize the alternative techniques for one processing step ([13] - adapted and modified from [14]).

6. Fibre morphology

a) Single Fibre versus Fibre Bundle

The bast fibres, for example hemp, that are extracted from the plant stem (see Figure 5), are referred to as 'fibre bundles'. It is generally these 'fibres' that are subsequently used in technical applications such as cordage, textiles or composites. The dimensions of the fibre bundles vary considerably, but are generally many centimetres to over a metre in length and from a few tens of micrometres in thickness to over 1 mm. The fibre bundles themselves consist of a collection of smaller fibres cemented together with various polymeric substances to form the bundle. These smaller fibres are the individual cells and are generally referred to as 'single fibres', or 'ultimate fibres'. These too vary in length and thickness, but are clearly far smaller than the fibre bundles. Figure 9 shows the fibre bundles and single fibres in flax (*Linum usitatissium* L.) and as may be clearly seen from the photomicrographs, the single fibres have relatively regular form and much smaller dimensions than the fibre bundles. Isolating the fibres bundles is generally accomplished using mechanical separation techniques, whereas to separate the fibre bundles into single fibre normally requires a chemical or enzymatic approach.

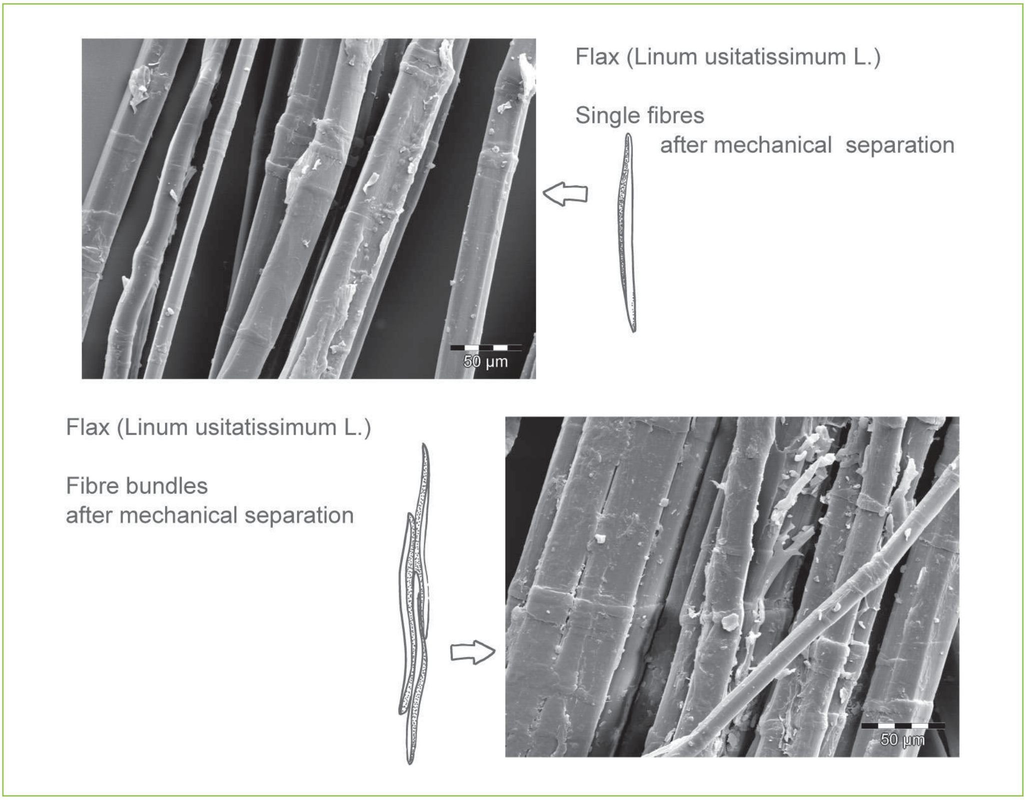


Figure 9: Scanning electron micrographs of single flax (*Linum usitatissimum* L.) fibres (upper image) and flax fibre bundles with different thicknesses and a single fibre in front (lower image).

b) Cross-sections

When the transverse section of a plant fibre is viewed, clear differences can be seen between the fibre types. Figure 10 shows, schematically, the cross-sections of cotton and coir fibres as well as the aforementioned flax and hemp bast fibres. As may be noted, the morphologies of these entities differ considerably and it can be observed that the fibre bundles consist of a larger number of individual fibres. These individual fibres can be viewed as a long hollow tube (in reality the cross-section is generally polygonal and rarely regular), where the cell wall surrounds a central void space known as the lumen.

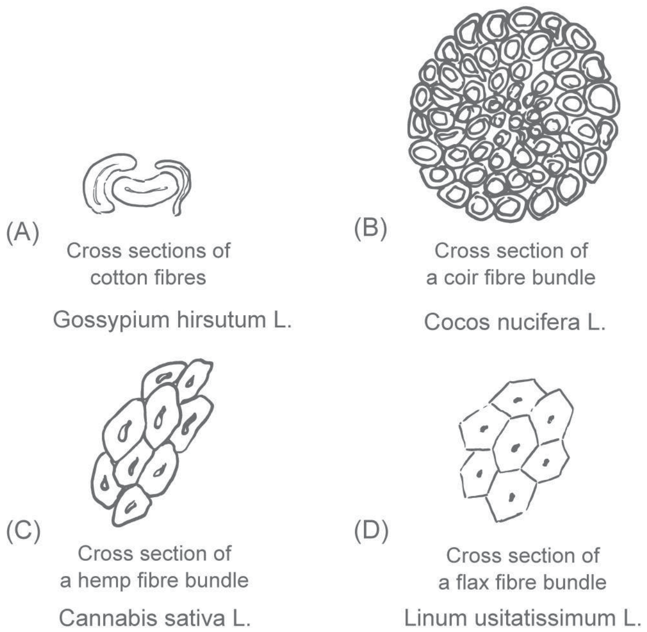


Figure 10: Schematic representation of the cross-sections of cotton fibres and fibre bundles of coir, flax and hemp.

c) Fibre Length & Thickness

Just as the morphologies of the fibres differ, so do their dimensions. As can be seen from Figure 11, the length of both fibre bundles and single fibres vary considerably depending upon the fibre type. Hemp, flax, ramie and jute all possess long fibre bundles (greater than 10 cm and up to 5 m) that have relatively small diameters. This would facilitate the spinning of these fibre bundles into yarn that can subsequently be formed into textiles for composite purposes (Figure 12). These long and thin fibre bundles also have very high aspect ratios, which is one of the requirements for good reinforcing efficiency. Although clearly much shorter than the fibre bundles, the single fibres of hemp, flax, ramie and jute also have relatively high aspect ratios, suggesting that they would provide efficient composite reinforcement.

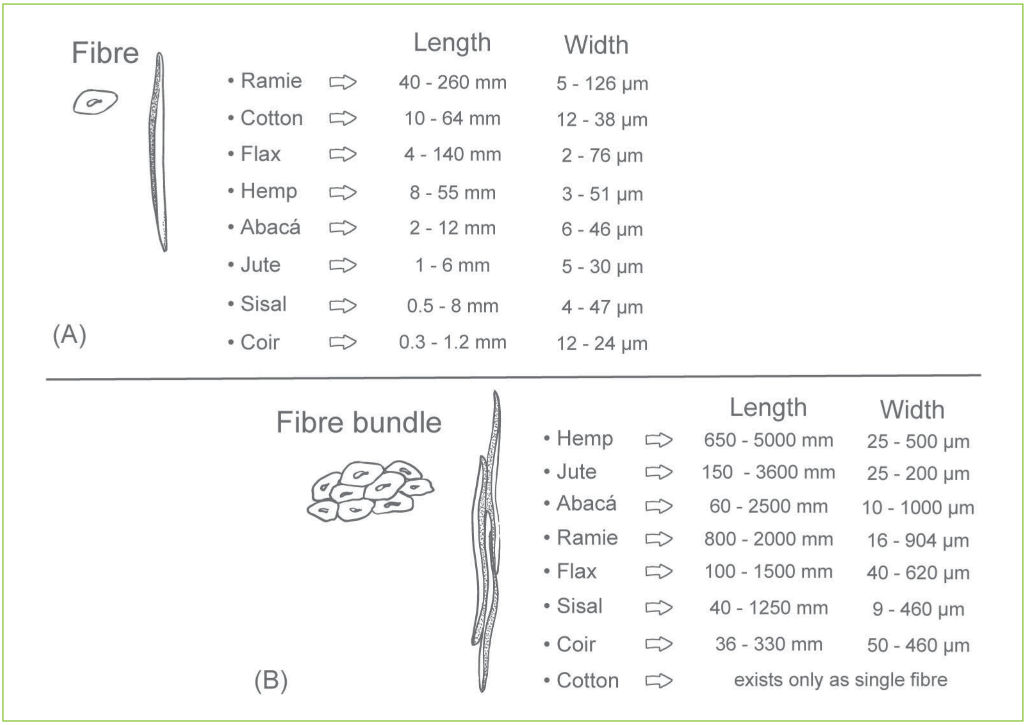


Figure 11: (A) Length and width values of single fibres. (B) Length and width values of fibre bundles (values taken from [10]).

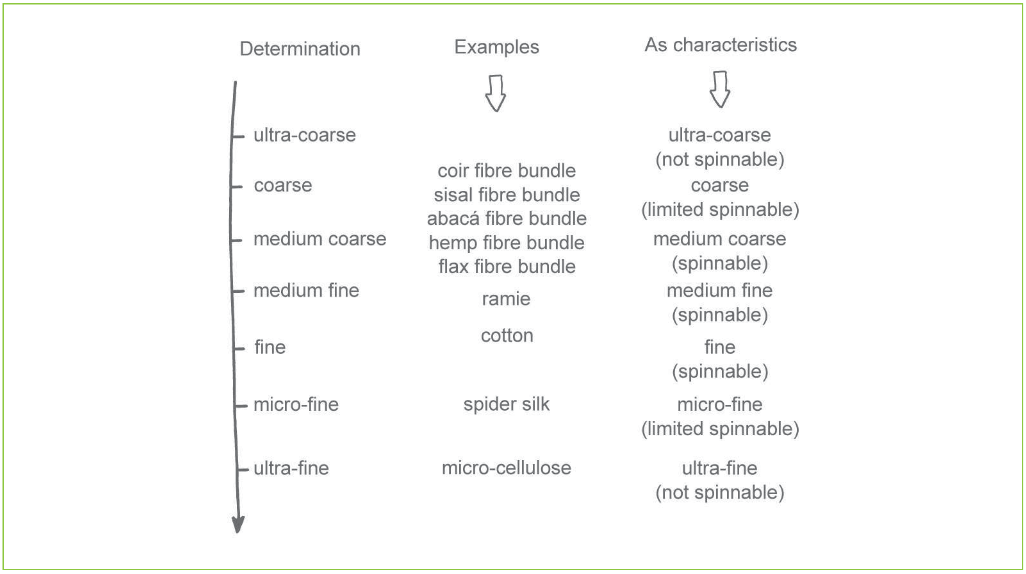


Figure 12: (A) Determination of fibre and fibre bundle fineness (based on the definition for fibre fineness from [15]).

7. Cell wall structure & Properties

a) Arrangement of microfibrils in the cell wall

The cell wall structure of a plant fibre is analogous to the laminate structure of a synthetic fibre reinforced composite; the arrangement of the microfibrils in the plant cell wall is rather intricate and this well-ordered structure largely controls the properties of the fibre itself. Figure 13 shows the cell wall organization of plant fibres that have different microfibril (MFA) angles.

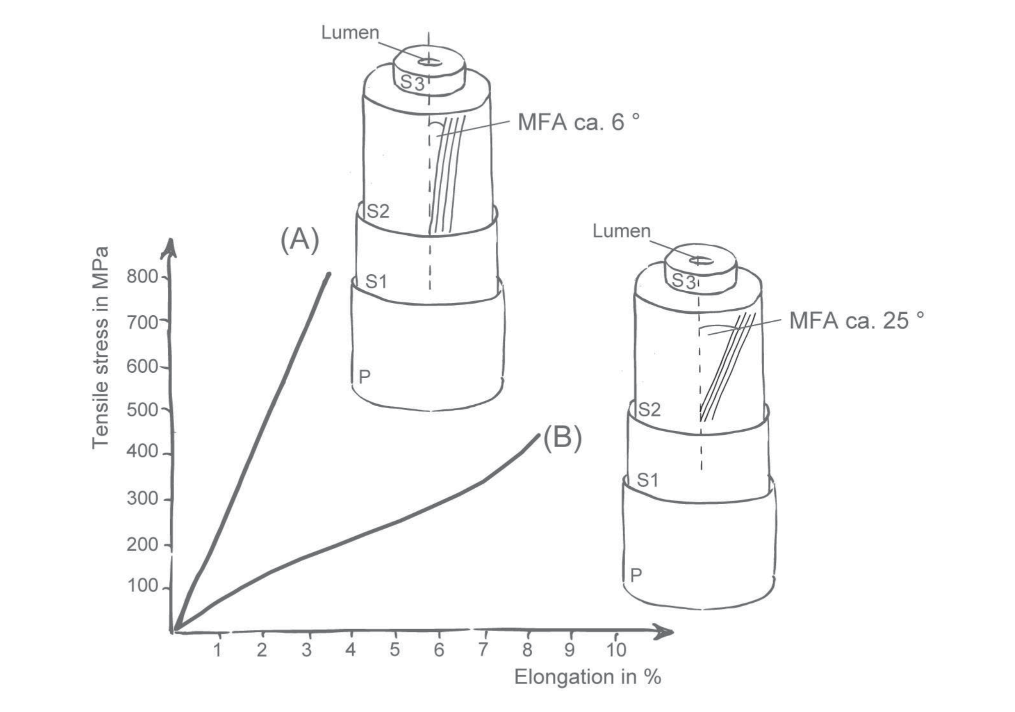


Figure 13: Influence of the cellulose microfibril angle (MFA) on the mechanical properties of plant fibres. (A) A fibre like hemp. (B) A fibre like cotton.

The cell wall itself consists of a primary (P) and a secondary wall. The secondary wall is itself sub-divided into further layers known as the S1, S2 and S3 layers (Figure 13). The very thin primary wall lying at the outside of the fibre is adjacent to the middle lamella (the interstitial region between adjacent cells in the fibre bundle) and consists of a random arrangement of microfibrils [6]. The middle lamella comprises binding substances holding the fibres together. In wood, the middle lamella (ML) consists mainly of lignin, whilst in flax, mainly pectin is to be found in the ML. In hemp both pectin and lignin are present. The outermost and innermost layers of the secondary wall, the S1 and S3 layers represent a small proportion of the cell wall. In these layers, the microfibrils are arranged in two distinct spirals; one left-handed and the other right-handed ('Z' and 'S' helices). The microfibrils in the S2 layer, which forms the bulk of the secondary cell wall, are aligned parallel to one another in a single steeply inclined helix. Since the S2 layer accounts for the greatest proportion of the cell wall, it follows that the angle (the MFA) between the microfibrils in this layer and the fibre axis will strongly affect the tensile properties of the fibre. As can be seen from the schematic diagram shown in Figure 13, an increase in the MFA from 6° to 25° dramatically affects the behaviour of the fibre when subjected to an axial tensile stress. In bast fibres, the MFA is generally rather low; in hemp for instance it has been reported to be less than 10° [16] and as such much of the stiffness of the cellulose molecule will be conveyed to the fibre. Moreover, bast fibres such as flax and hemp contain a high proportion of cellulose (Table 1), which is the ultimate high-strength, high-stiffness reinforcement in all plant fibres. The high percentage of cellulose in the secondary cell wall, coupled with the low MFA, confers excellent tensile strength and stiffness on such fibres. An important further consideration is the volume of the cell wall, relative to the volume of the fibre. Thygesen et al. [17] have for instance observed that in some hemp fibres, the remaining lumen space in mature fibres amounts to less than 10% of the fibre cross-sectional area. A large proportion of cell wall material would indicate good mechanical properties.

b) Mechanical Properties

Morphological, chemical and micro-structural characteristics will largely affect the mechanical properties of the fibres and fibre bundles. The properties of the fibres will, in turn, affect the properties of the final composite. However, measuring the mechanical properties of fibres and fibre bundles is not an easy matter at all. To understand and interpret the mechanical properties of plant fibres correctly, it is essential to bear in mind several important factors which strongly influence tensile properties, including: (i) the testing speed, (ii) the fibre diameter, (iii) the gauge length, (iv) the number of specimens tested and (v) the entity (i.e. ultimate fibre or fibre bundle) which is being tested. Many authors have reported on the influence of these aforementioned factors and an overview can be found in [10]. In determining the Young's modulus of the fibre, how fibre strain is measured is also of great importance. Figure 14 illustrates schematically how variation in the measured tensile properties can arise from: (i) testing single fibres rather than fibre bundles and (ii) the differences in gauge length.

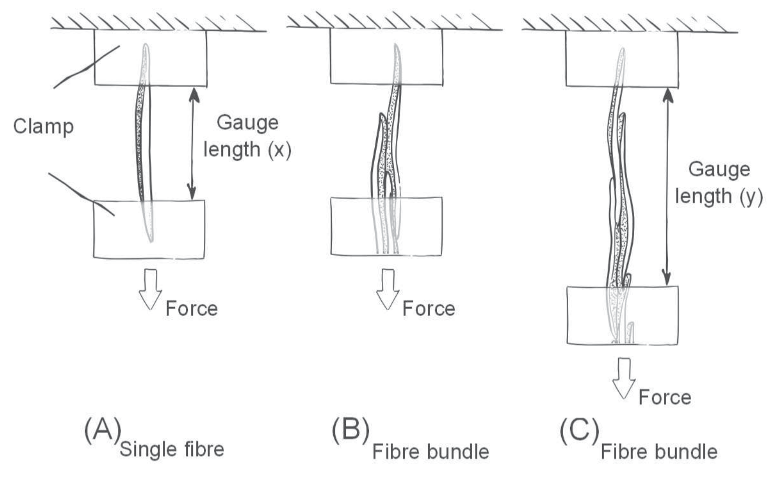


Figure 14: Various testing methods to test the tensile properties of plant fibres and fibre bundles. (A) Single fibre fixed in clamps at a gauge length (x). (B) A fibre bundle prepared for tensile testing with the same gauge length (x) as the single fibre. (C) Fibre bundle with a greater gauge length (y).

- Table 2 -

Mechanical properties of selected natural fibres. Naturally, the measured properties show a range. To give the reader an overview, the most frequently published data are shown (mean values taken from [10])

Properties	Flax	Hemp	Jute	Ramie	Sisal	Abacá	Coir	Cotton
Tensile Strength in MPa	700	800	500	800	600	600	200	450
Young's Modulus in GPa	70	65	30	65	12	50	5	8
Elongation at break in %	3	3	1.8	3	3	4	30	8
MFA in °	5–10	2–6	7–10	7–10	10–25	10–12	30–49	20–30
Density in g/cm³	1.4 – 1.52	1.4 – 1.6	1.3 – 1.5	1.5 – 1.56	1.0 – 1.5	1.4 – 1.5	1.15 – 1.5	1.5 – 1.6

c) Factors Affecting the Fibre Properties

Despite the excellent potential shown by plant fibres in terms of their mechanical properties, these are generally not realised in practice. Bast fibres, in particular show very good tensile mechanical properties, however, during processing the fibres can be damaged through the formation of dislocations that can reduce their properties. These dislocations (also sometimes referred to as kink-bands, micro-compressive defects or nodes), are presented in Figure 15.

It has been shown that these defects can lower the stiffness of the fibre [19] and lead to non-linear tensile deformation behaviour [20]. When bast fibres are used as reinforcement in thermosetting polymer matrix composites, the presence of dislocations can lead to stress concentrations at the interface and in the matrix, resulting in microstructural damage [21] and this in turn can lead to yielding behaviour at low levels of stress and strain [22] and to low composite toughness. Clearly these will have a direct impact on the application of natural fibre reinforced composites.

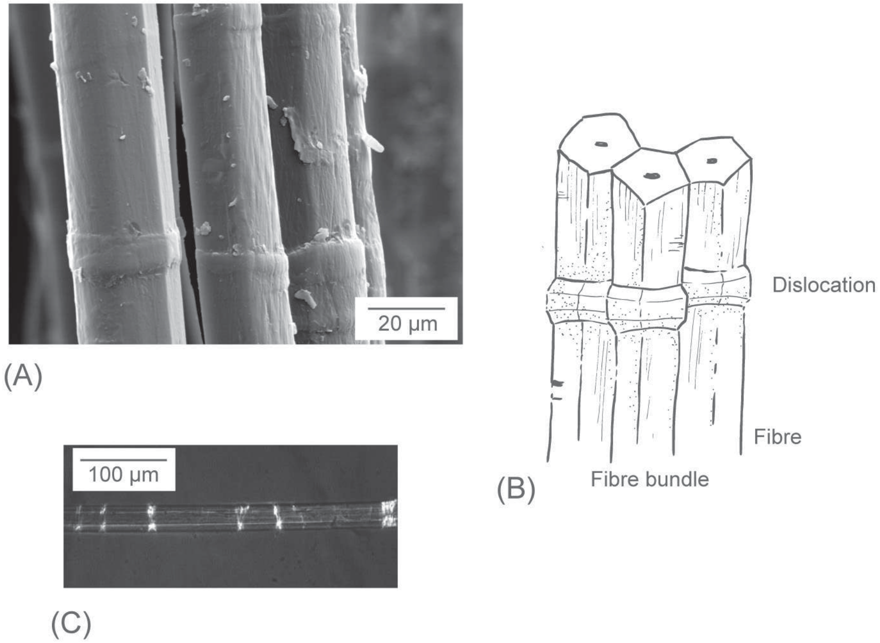


Figure 15: (A) Scanning electron micrograph of dislocations in a flax fibre bundle. (B) Schematic representation of dislocations in a flax fibre bundle. (C) Dislocations in flax, shown as bright zones crossing the fibre when viewed under polarised light in an optical microscope.

Another significant factor that can affect the properties of all plant fibres is moisture. Accessible hydroxyl (-OH) groups present in the cell wall polymers of plant fibres (Figure 5) are able to attract water molecules and bind them through hydrogen bonds, rendering the fibres hydroscopic. Hydroxyl groups in the crystalline cellulose core of the microfibril form inter- and intra- molecular hydrogen bonds that maintain the crystal structure and provide some lateral stability to the cellulose chains. Since the -OH groups in the crystal core of the microfibril are engaged in inter- and intra- molecular hydrogen bonding, they are unavailable for binding water molecules. Accessible hydroxyl groups on the surface of crystalline cellulose and in the hemicelluloses and lignin that surround the crystalline core are, however, able to bind with water molecules. Water molecules can continue to be adsorbed by the polymers in the cell wall, to a point where the cell wall becomes saturated. Further water can then only be found in the form of liquid water in the void spaces in the cell (the lumen). This liquid water is known as “free” water, whilst the water in the cell wall is known as “bound” water. The total amount of water in the plant fibre is known as its moisture content (MC) and is generally expressed as the mass of water in the plant fibre relative to its completely (oven) dry mass. When placed in certain conditions of relative humidity (RH) and temperature, the fibre will establish an equilibrium MC with those surroundings; when relative humidity is low, the fibre moisture content is low and conversely, when the relative humidity is high, the fibre EMC (equilibrium MC) will be high. The relationship between RH and EMC is not linear, however, and is also dependent upon the moisture history of the fibre.

Changes in the fibre's MC leads to dimensional changes occurring mainly in the transverse sense; when moisture is lost, the fibre shrinks, and when the moisture content increases, it swells (see Table 3).

- Table 3 -
Behaviour of some natural fibres in moisture conditions (values taken from [10 & 23]

Properties	Flax	Jute	Sisal	Cotton
Absorption regain in % at 65% relative humidity and 20 °C	7–12	8.5–17	10–22	7–25
Transverse swelling in %	20–25	20–22	18.20	7–20
Axial swelling in %	0.05-0.2	0.37		1.1–2.8
Volume swelling in %	29.5	44–45	39.5	34–44
Water retention in %	50–55	25–35	30–45	45–50

Thus the fibre will "move" when the ambient RH fluctuates. This can be problematic when the fibre is used as composite reinforcement, since the dimensional changes can lead to tensile stresses normal to the interphase, which can result in fibre-matrix debonding if the adhesion between fibre and matrix is not sufficiently strong. Another effect of moisture is to alter the mechanical properties of the fibre (this is partly the reason why wood is dried prior to use: dried wood is stronger and stiffer than "green" wood). In general, an increase in MC leads to a decrease in mechanical properties. High moisture contents, close to the fibre saturation point (FSP) can result in biological degradation of the fibre and to a rapid loss in mechanical properties. As can be seen from Figure 16, fibres react differently depending on the chemical and micro-structure in changing climates. For example, whilst wool as a hydroplastic fibre shows a decrease of strength if the humidity increases, flax fibres are stronger at higher values of humidity compared to the standard climate at 65% relative humidity.

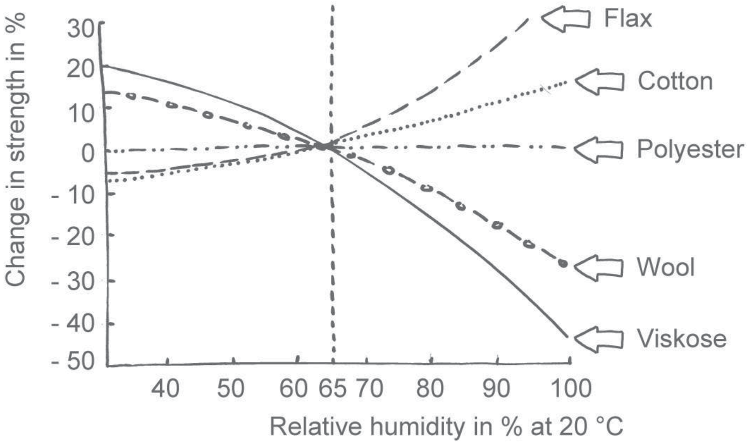


Figure 16: Change of the fibre strength as a function of relative humidity at 20 °C; values related to standard conditions at 65% relative humidity (adapted from [23]).

To reduce moisture sorption (and so improve dimensional stability), to enhance fibre-matrix adhesion and to reduce biodegradation, natural fibres are often modified by chemical or physical means in order to render them more suitable as composite reinforcement.

8. Testing & Standards

As described in the previous section it is essential to standardise the testing conditions to get reproducible results. As shown in Figure 16, for example the influence of the humidity has a non-negligible influence on the test results. Based on this knowledge, it is very important to condition the fibres prior to testing in a defined and constant climate. Within the fibre and textile community it is common to condition the fibres for at least 24 hours at 20 °C and 65% relative humidity according to the standard DIN EN ISO 139 (Textiles - Standard atmospheres for conditioning and testing) or similar standards like ASTM D-1776.

There are many different grading systems and standards specifically introduced for different kinds of natural fibres [24]. In this subsection we will focus our brief description on flax.

The fineness (a measure of linear density and indirectly a measure of the cross-sectional dimensions of the fibre) of flax ultimate fibres or fibre bundles can be measured by different methods. The most common method (and the only internationally standardised one before the year 2000) is a permeametric method, defined in the ISO 2370 Standard Test Method: "Textiles – Determination of fineness of flax fibres – Permeametric methods" from 1980. The method is based on measuring the pressure drop across a wad of fibre of known mass. Finer fibres impede airflow through the wad and so the pressure differential is greater. However, to utilise this method, the system must be calibrated using fibre of know linear density. Calibration of the testing equipment is performed with a series of flax fibre bundle grades (hackled flax), purchased from the Institut Francais Textile – Habillement, Lille, France.

In the late 1990s, representatives of government, industry and academia actively began developing standards for flax fibre through ASTM International. Subcommittee D 13.17 (Flax and Linen) was officially formed in 1999. The result of these activities was a series of standards which have been approved as test methods for flax (see Table 4). [25]

- Table 4 -
ASTM flax standards to date under subcommittee D 13.17 of ASTM International [25 & 26]

Title of standard	Designation	Approved
Standard Terminology Relating to Flax and Linen	D-6798-02	2002
Standard Test Method for Color Measurement of Flax Fibre	D-6961-03	2003
Standard Test Method for Assessing Clean Flax Fibre Fineness	D-7025-04a	2004
Standard Test Method for the Measurement of Shives in Retted Flax	D-7076-05	2005

Recently, there have been on-going standardisation activities for flax-fibre composite applications in France (see Table 5). These activities are organised by AFNOR (afnor.org) which is an international services delivery network with strong activities in the areas standardisation and certification.

- Table 5 -
French flax standards (AFNOR) for flax in composite applications

Title of standard	Designation	Released	Status
Reinforcement fibres - Flax fibres for plastic composites - Part 1: terminology and characterisation of flax fibres	XP T25-501-1	July 2010	Experimental standard
Reinforcement fibres - Flax fibres for plastics composites - Part 2: determination of tensile properties of elementary fibres	XP T25-501-2	October 2009	Experimental standard
Reinforcement fibres - Flax fibres for plastic composites - Part 3: determination of tensile properties of technical fibres	XP T25-501-3	July 2010	Experimental standard

The concept of standardisation for testing natural-fibre properties will become more and more important in the composites community. Process and structural simulation of natural-fibre-reinforced plastics can only produce useful results if they are based on reliable models and data as well as natural fibres of predictable and reliable quality. According to Harig et al. [28] these conditions are met by the:

- the provision of reproducible fibre qualities by fibre supplier, based on a quality management system that has been put in place along the whole value-added chain, with reproducible proof of origin, and
- the objective determination of accurate fibre properties for the simulation and calculation of the final composite part.

With increasing production of natural-fibre composites, the demand for adequate fibre testing methods has evolved. As an orientation aid for industry in this sector, recommendations have been set up as part of the N-FibreBase project (www.n-fibrebase.net). These test recommendations for fineness, strength, length, colour, fogging, odour and content of impurities are summarised in references 10 & 29. These recommendations were developed in close coordination with the working group on natural-fibre-reinforced polymers of the German Federation for Composite Materials (AVK-TV).

9. Fibres & Composites

As described in the previous sections the type of fibre, its morphology, structure and chemistry will all play a part in determining the final fibre/fibre bundle properties and characteristics. However, the composite properties are not only influenced by the specific fibre properties, but are also very dependent on the bonding between the fibre and the polymer matrix. In this context, the so-called interphase between fibre and polymer matrix plays an essential role (see Figure 17). The interphase itself is a three-dimensional entity with a heterogeneous structure, and marks the transition zone between fibre and matrix. Within this transition zone the properties altered from the fibre properties to matrix properties. Starting from the fibre, the interphase expires at the point where the properties are those of the matrix.

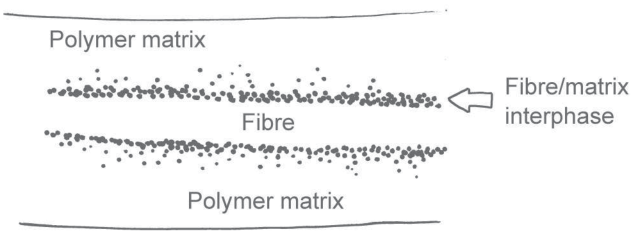


Figure 17: Scheme of the interaction between a reinforcing fibre and a polymer matrix via the connecting interphase.

Optimisation of the interphase between plant fibres and polymer matrices is key to obtaining composites with superior properties. To combine, for example, jute fibres with polypropylene (PP) as a matrix, phase compatibilizers are necessary in order to create a chemical bond between the polar fibre and the non-polar PP. Doana et al. [30] reported that the addition of 2% by mass of a compatibilizer to a PP matrix significantly improved the interphase with jute fibres and improved the tensile strength and Young's modulus of the composite too. The authors summarized that this was mainly due to the improvement of the interphase, which can be achieved using maleic anhydride grafted polypropylene (MAHgPP) as the coupling agent. In MAHgPP, the maleic anhydride group can couple with the hydrophilic fibre surface; the polypropylene chain can then interact with the polypropylene matrix. [30] The same effect on the interfacial shear strength (IFSS) were published for flax-fibre-reinforced polypropylene by Bos [31], who reported that the IFSS values for a combination of flax with pure PP are all lower than for flax with MAPP. It was concluded that due to the presence of MAPP as a coupling agent, the interphase between fibre and polymer matrix is improved.

In the theoretical model shown in Figure 18 the coupling agent MAHgPP acts as a compatibilizer to promote better adhesion between the polar natural fibres and the non-polar polypropylene by the formation of an ester bond and a hydrogen bond.

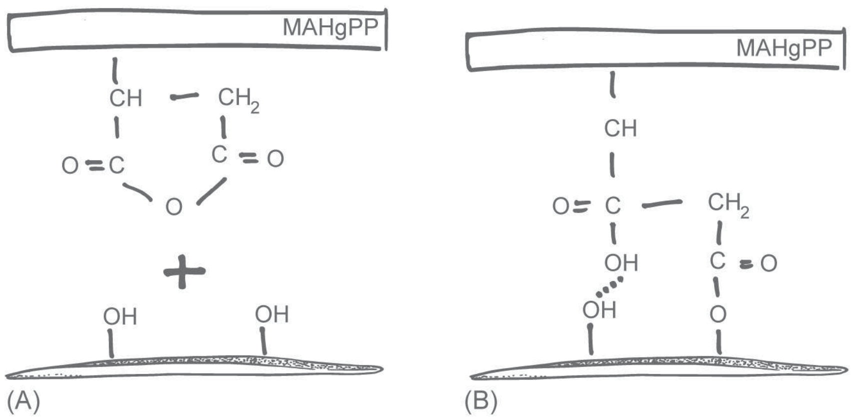


Figure 18: Possible structure of the interphase between a cellulose fibre and polypropylene using maleic anhydride as the coupling agent.

How the fibre properties subsequently affect the properties of the final composite is not always straightforward. The properties of a composite are heavily influenced by the fibre volume fraction, the alignment and packing arrangement of the fibres and the fibre/matrix interphase. These factors will in all probability predominate. Thus, the effect of the changing fibre characteristics on the properties of a composite as shown in Table 6 is only intended to give the reader a very general picture of the influences of fibre properties on composite properties.

To conclude, we believe that natural plant fibres have a bright future with a realistic potential to find their way into a broader composite market. To reach this potential, in our opinion some important steps need to be taken, however. These steps include:

- optimised, gentle processing lines from cultivation to the final fibre in order to retain as much of the inherently excellent mechanical properties of the fibres;
- optimised, gentle composite processing techniques to compound the fibres into the polymer matrix without thermal degradation and without a critical reduction in the aspect ratio of the fibre;
- improvement and engineering of the interphase between fibre and polymer matrix;
- establishing testing standards and databases for natural fibres and natural fibre compounds;
- development and realisation of simulation models for process simulation and structural calculation of natural-fibre composites.

- Table 6 -
Influence of fibre properties and characteristics on composite properties

Fibre properties	Composite properties		
	Strength	Young's' Modulus	Impact
Length ↑	+	≈	++
Diameter ↓	+	+	+
Strength ↑	++	++*	+
Young's Modulus ↑	++*	++	--
Elongation ↑	-**	-**	++
Interphase ↑	++	+	-
Dislocations ↑	-	-	--

\- decrease / -- strong decrease / + increase

++ strong increase / ≈ low influence

* in general fibres with a high Young's modulus show high strength values and vice versa

** in general fibres with high elongation values show lower strength and Young's modulus values

10. Acknowledgement

Using mainly handwritten graphics, we have tried a new way of illustration in this chapter. Our special thanks to Anja Müssig (schnittreif) for her creative work. We would also like to thank Tanja Slootmaker (Faserinstitut Bremen e.V., DE) for the SEM micrographs of flax.

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- III - Architecture of textile reinforcements and properties of composites

Joris Baets,
Postdoctoral Researcher at the Department Metallurgy and Materials Engineering, KU Leuven, Belgium
Coordinator of the European Scientific Committee of CELC

Stepan V. Lomov,
Professor At Department Metallurgy and Materials Engineering,
KU Leuven, Belgium

"Textile" is defined as "originally a woven fabric, but the term 'textiles' is now also applied to fibres, filaments and yarns, natural or man-made, and most products for which they are the principal raw materials" (*Textile Terms and Definitions[1]*). Hence, textiles are fibrous materials. Fibres in a textile are assembled into yarns or fibrous plies, which are arranged to form a textile fabric.

Textile yarns, or tows, used in composite reinforcement, are characterised by:

- linear density of the yarns (measured in SI units *tex = g/km*) or number of fibres in the yarns,
- length of the fibres in the yarn (short or staple fibres, continuous *filaments*, etc.),
- twist of the fibres measured in *twists/m* (flat yarns with straight fibres are called *rovings*),
- their composition – *commingled* yarns can contain a blend of load-carrying fibres and thermoplastic resin in the form of short fibres or long filaments.

Textile reinforcements can be two-dimensional (2D) and three-dimensional (3D).

- 2D fabrics, which have only in-plane arrangement of the yarns and are thin, are normally used in laminated preforms.
- A fabric is classified as 3D if there is a certain structural arrangement of the yarns in the thickness direction, and the integrity of the fabric is maintained with yarns for which direction deviates significantly from the plane of the fabric. 3D fabrics normally have a considerable thickness, which is enough for the fabric to be used as one-layer reinforcement.
- A laminated preform can be stitched prior to the composite production; the stitched preform can be considered as an integral 3D reinforcement (Figure 1).

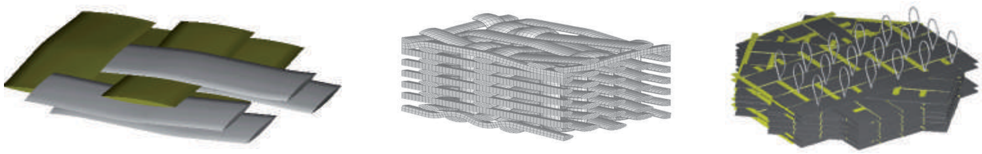


Figure 1: Laminated 2D (a), 3D (b) and stitched (c) preforms.

Woven preforms. A woven fabric is produced by interlacing of two orthogonal systems of yarns: warp (length wise of the fabric) and weft, or fill (width wise). The repeating pattern of the interlacing, or *weave*, for one-layered fabric is depicted by a checkerboard scheme (Figure 2). In such a scheme each column of squares represents a warp yarn, each row, a weft yarn. A square is painted black if the warp yarn goes over the weft, and white otherwise. Figure 2 shows the weaves most often used for composite reinforcements. Apart from the weave pattern, a woven fabric is characterised by:

- linear density or fibre count in the yarns,
- ends/pick count (number of warps per unit width and number of wefts per unit length of the fabric),
- areal density of the fabric.

A *balanced* fabric has equal parameters in warp and weft directions (= same yarns and same ends/picks count); a *quasi-UD* fabric has thick, tightly placed warp yarns interlaced by thin, sparse weft.

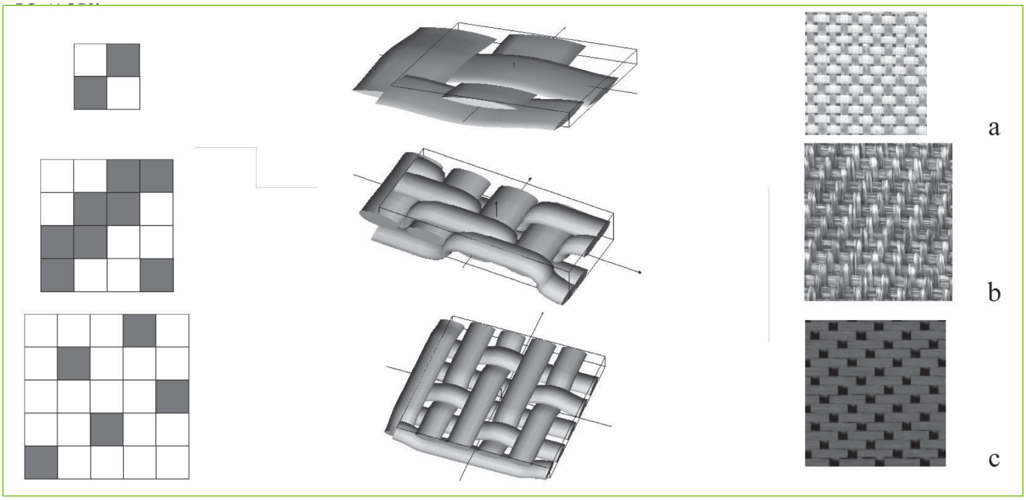


Figure 2: Weaves, 3D representations of the fabric repeat and examples of composite reinforcements: (a) plain weave, glass; (b) twill 2/2 weave, glass/polypropylene; (c) 5H satin weave, carbon. Arrows indicate the warp direction.

Braided performs

Braiding is the process of interlacing three or more threads in such a way that they cross one another in diagonal formation, as illustrated in Figure 3. Flat, tubular or solid constructions may be formed in this way. The most important parameter of a braid is the braiding angle (an angle between the yarns of two interlacing systems).

If a 3D-shaped mandrel with a variable diameter is used, then the take-up speed should be constantly adjusted to achieve a uniformity of the braiding angle. By varying the take-up speed, one can also achieve a certain variability of braiding angles along the preform, resulting in a desired variation of stiffness of the composite part. The practical range of the braiding angle is between 20° and 160°.

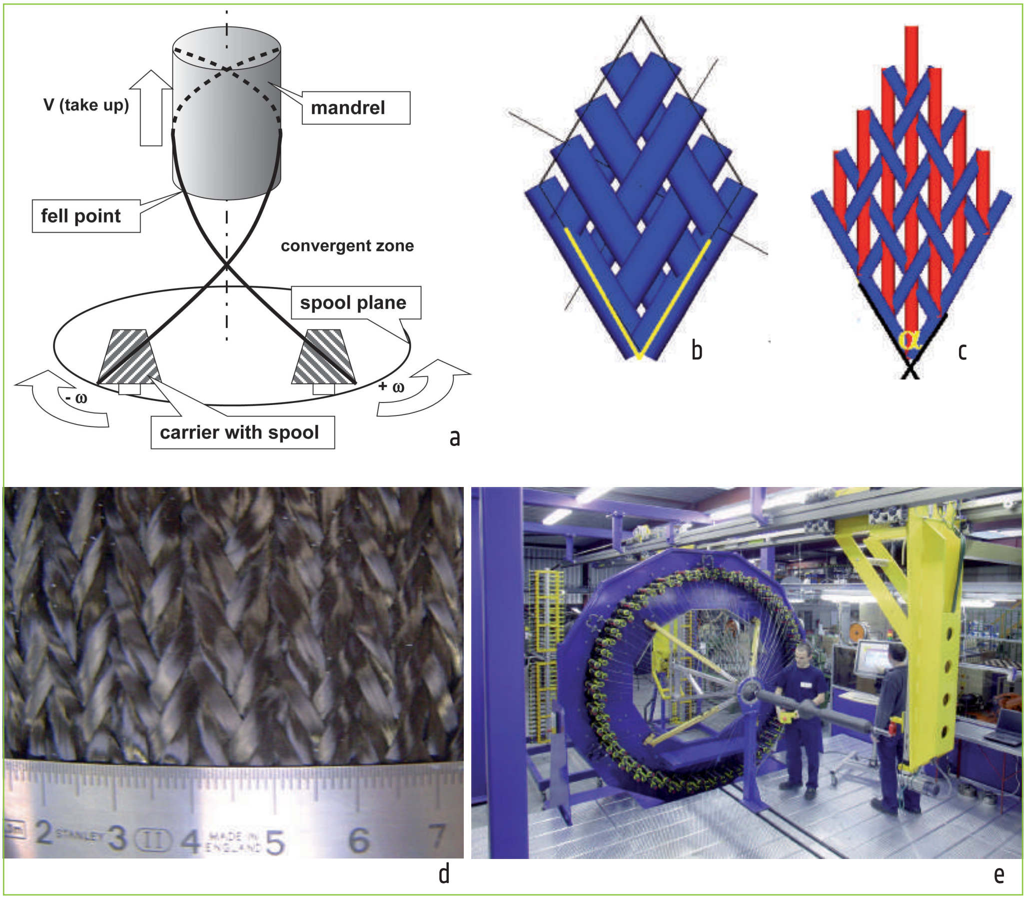


Figure 3: Braiding process: (a) scheme of a maypole braider; (b) definition of the braiding angle; (c) 3-axial braid 0°/+60°/-60°; (d) example of braid ; (e) braiding machine (Source: *Eurocarbon*).

Non-crimp fabrics (NCF) are designed to combine the unidirectionality of fibrous layers with the integrity of the preform, achieved by binding the layers together. European standard EN 13473 defines a multiaxial multiply fabric as "a textile structure constructed out of one or more laid parallel non-crimped not-woven thread plies with the possibility of different orientations, different thread densities of the single thread plies and possible integration of the fibre fleeces, films, foams or other materials, fixed by loop systems or by chemical binding systems. The threads can be oriented parallel or alternating crosswise. These products can be produced on machines with insertion devices (parallel-weft or cross-weft) and warp knitting machines or chemical binding systems".
Binding the plies together by warp-knitting can be deliberately made in such a way, that the stitching yarn pierces the plies in between the laid threads. This would result in open preform architecture (Figure 4).

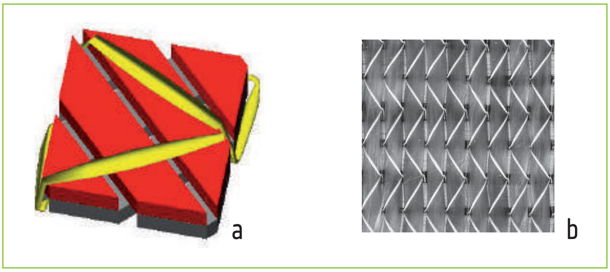


Figure 4: Open non-crimp preform:
(a) structure of an open non-crimp preform; (b) example of open non-crimp preform.

Alternatively, wide threads (flat tows) are laid very close together, forming continuous fibrous plies. The plies are bound by warp-knitting (Figure 5), with piercing sites positioned on the surface of the preform according to the needle spacing, without any connection to the tow positioning. Needles pierce the fibrous plies (probably in the middle of the laid-up tows), distorting them locally. This results in a preform construction close to an ideal laminate composed of unidirectional uniform plies.

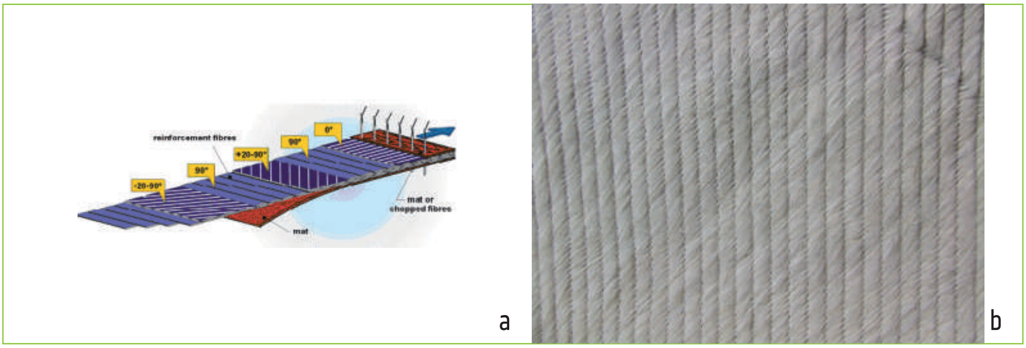


Figure 5: Non-crimp fabrics: (a) scheme of the production process (source: http://iparamaxc.de); (b) examples of NCF: biaxial +45/-45 flax.

Importance of crimp for composites

The internal structure of a textile reinforcement determines the performance of a consolidated composite: when a (global) load is applied, the local stresses and deformations will depend on the local orientation of fibres which is imposed by the reinforcement architecture. Hence the (local) yarn waviness will influence the global stress-strain response in the elastic regime, but also defines whether damage will be initiated in that particular location and whether it will propagate.

The waviness of a yarn is measured by its *crimp* $c = \frac{l - l_0}{l_0}$

where l is the length of the yarn in the unit cell, l_0 is the straight distance between end points of the yarn (Figure 6). Crimp is connected to the inclination of the yarn, which defines the reduction of stiffness of the composite.



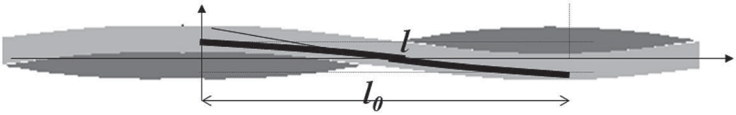
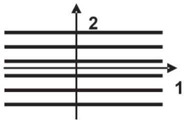
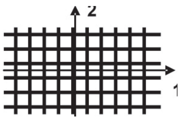
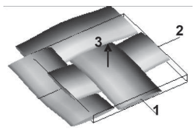
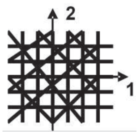
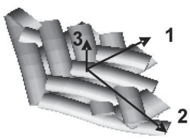
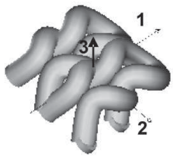



Figure 6: Definition of crimp.

Table 1 gives typical values for the stiffness of different flax textile composites, calculated using a formula which takes into account the local orientation of the yarns, in comparison with the properties of a UD material and of UD-based cross-ply laminates.

- Table 1 -
Typical values of engineering stiffness parameters (E, G, «nu») of UD, cross-ply and textile flax/epoxy composites. Fibre volume fraction 60%.

Reinforcement	Image and coordinate system (for laminates: Axis *3* is normal to the image plane)	flax/epoxy		
		E11, E22 GPa	G12, GPa	ν 12
UD		39.5 4.4	2.4	0.311
Cross-ply 0/90		23 23	2.4	0.061
Plain woven, crimp 1.5%		15 15	2.2	0.023
Quasi-isotropic 0/45/-45/90		17 17	6.7	0.283
Tri-axial braid 0/60/-60, crimp braiding yarns 1%		17 15	5.8	0.267
Knitted jersey		6.5 6.0	2.7	0.301

Fibre and matrix data used in the calculations:

Flax: longitudinal modulus 64 GPa; transverse modulus 5 GPa; Poisson coefficient 0.25

Epoxy: Young's modulus 3.0 GPa, Poisson coefficient 0.4

A UD-composite with 60 vol% of flax fibres in an epoxy matrix reaches a high stiffness of 39.5 GPa in the fibre direction, but a low stiffness in the direction perpendicular to the fibres (4.4GPa).

A cross-ply laminate, composed of UD-layers and hence with zero crimp, has the same stiffness in both 0° and 90° direction (23 GPa). The drastic effect of the crimp is visible when we compare this with the stiffness of a woven flax composite, even with a very low crimp of only 1.5% (only achievable with yarns with very low or no twist, see next paragraph). The stiffness drops by 30% to only 15 GPa. The effect of yarn crimp can further be shown by comparing the two quasi-isotropic reinforcement architectures: the UD-layer based 0/90/±45-material reaches 17 GPa, in both 1 and 2 directions, whereas in the 0/±60 braided reinforcement, the yarn crimp reduces the stiffness to 17 GPa in the 1 direction and 15 GPa in the 2 direction; the crimp even has a consequence, in that the quasi-isotropy is lost.

Finally, the knitted fabric has fibre waviness both in plane and out-of-plane, reducing the stiffness to only 6.5 GPa.

Importance of twist for composites

Flax and hemp fibres have a limited length, which is different from the continuous synthetic fibres. By spinning the fibres a continuous yarn is produced from the flax and hemp fibres. During the spinning process the fibres are twisted in order to make the bundle stronger. This increases the strength of the dry fibre bundle because of the increased friction and entanglement between the fibres. However, this twist reduces the fibre alignment and thus has a negative influence on composite stiffness.

In textile technology (the traditional market for flax and hemp), the amount of twist is indicated by the number of turns per meter. To evaluate the effect on composite stiffness, it is better to use the twist angle, as this parameter can be directly related to fibre (mis)orientation. Several models do use twist angle to predict the properties. The twist angle is defined as the angle that the fibres (in the fibre bundle) make at the surface with respect to the axis of the fibre bundle. Figure 7 schematically shows how the twist angle is calculated if the number of turns (1/h) and the fibre bundle diameter (D=2R) are known. In an ideal twisted yarn with a circular cross-section, the fibres will follow a helicoidal path. By unfolding these fibres, the twist angle can be calculated.

$$\tan \alpha = \frac{2\pi R}{h} \qquad (1)$$

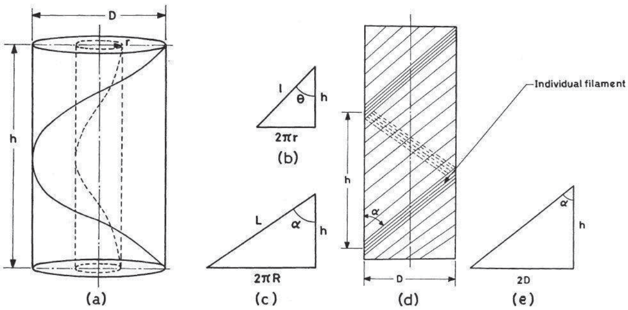


Figure 7: Geometry of an ideal twisted yarn (a) uniform cylindrical yarn; (b) twist angle at radius r; (c) twist angle at the surface [2].

Influence of twist on mechanical properties

The introduction of twist leads to a lower performance of the fibres. There are different models which take into account the effect of the misorientation of the fibres on the composite stiffness. Of course, a higher amount of twist – in fact a higher twist angle – leads to a lower stiffness.

In the following graph (Figure 8) the decrease in stiffness for an UD-composite made of impregnated flax fibre bundle with increasing twist is shown. It can be seen that with a twist angle of 20°, the stiffness already decreases by 50%. This means that for some traditional textile flax yarns with twist angles even higher than 20°, the stiffness is very limited. The models used for these calculations have been verified, and the test results for flax fibre bundles with different amount of twist confirm this model.

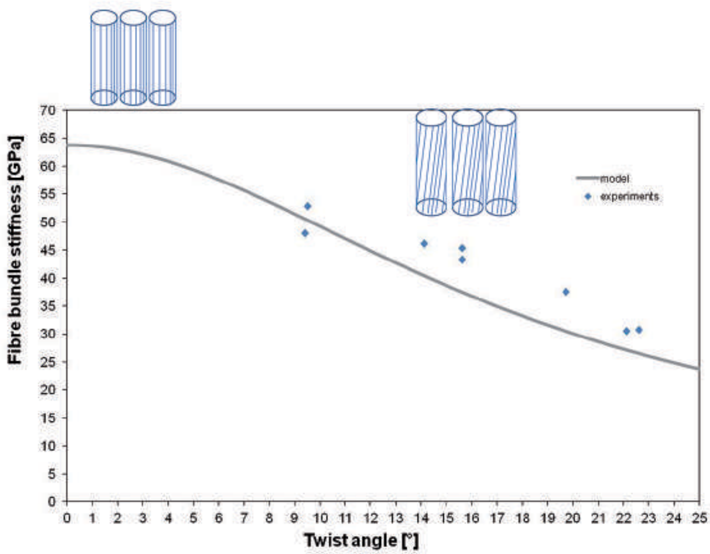
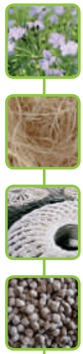


Figure 8: Influence of the twist angle on the stiffness of UD composite with flax yarns. Experimental values are also shown. The initial value is for a UD flax composite using yarns without any twist. The other values are for UD-composites using yarns with increasing degree of twist.



In the textile world, the number of twists is normally used instead of the twist angle. Because the twist angle increases with the number of twists as well as with the diameter of the yarn, a bigger influence on the stiffness will be found in thicker yarns. This can be seen in Figure 9.

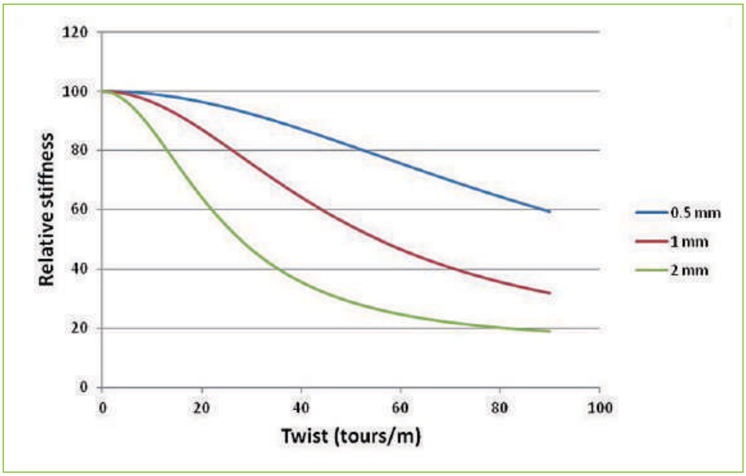


Figure 9: The relative influence of the amount of twist on the stiffness of a UD composite with twisted yarns for different yarn diameters.

Influence of twist on the amount of crimp

As seen above, highly twisted yarns have a direct negative effect on the composite properties. When these yarns are used in a weave, there is even an extra negative effect. Because of the twist the yarns are round, which leads in a weave to a higher crimp. This is opposite to the very flat rovings of glass and carbon, where the crimp can be drastically reduced. The higher crimp with twisted yarns leads of course to a lower stiffness because of a higher misorientation inside the yarns, but also out-of-plane.

Calculations to show the effect are made with the following data:

- a high-twist yarn, where the high twist results in a circular section, and in a UD-composite, stiffness of 70% of the maximum stiffness (=no twist, see Figure 8);
- a low-twist yarn, where the low twist leads to an elliptical shape with the ratio of 1/10 for the short and long cross-sections; this yarn results in a UD-composite stiffness of 90% of the maximum stiffness [3];
- epoxy matrix with stiffness of 3 GPa;
- a 40% fibre volume fraction.

Figure 10 shows the strong impact of crimp on the stiffness.

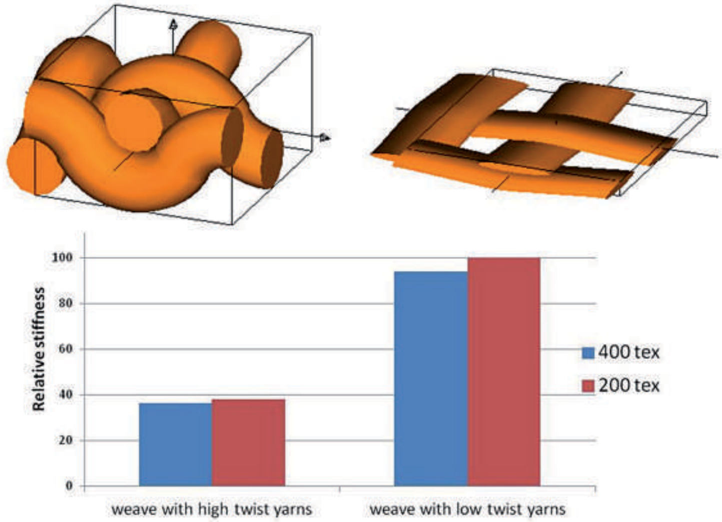


Figure 10: Relative stiffness of different weaves. The influence of the twist and the crimp is shown for yarns with two different linear densities.

Influence of twist on impregnation

The introduction of twist leads to circular yarns. When a higher twist is present in a yarn, the yarn becomes packed more densely. This very close packing of the fibres in the highly twisted yarns leads to a more difficult impregnation. Therefore, the yarns will still be present as round yarns, with only a limited impregnation.

When low twist yarns are used, the packing is less dense and the yarns are more open to impregnation. After impregnation, these yarns are less round and barely recognisable. So, to improve the impregnation and therefore the mechanical properties of the composites, it is important that the yarns have a low twist level.

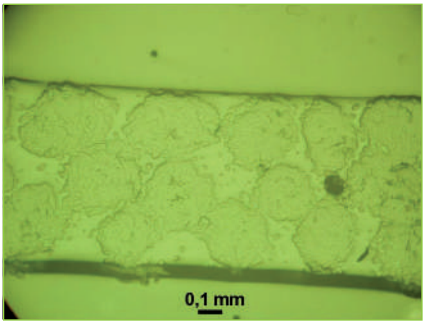


Figure 11: Microscopy of a UD composite made with flax yarns, the yarns are still very clear and barely impregnated.

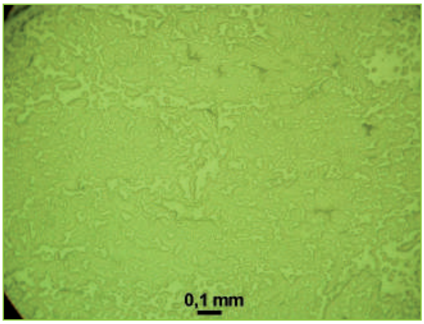


Figure 12: Microscopy of a UD composite made with flax rovings with low twist. The rovings are no longer recognisable.

Conclusion

The fibre architecture has a huge influence on composite properties like stiffness and strength. The effect of the orientation of the fibre is present with all types of fibres (synthetic or natural fibres). However the effect of twist, which is always present in flax and hemp yarns, is only present within the natural fibres. The presence of twist leads to lower mechanical properties, due to three effects:

- misorientation of the fibres due to the twist,
- higher crimp values due to the very round yarns,
- less effective impregnation due to the very dense structure of twisted yarns.

In recent years, guided by the CELC and its European Scientific Committee, the European flax and hemp industry has been developing new types of textile preforms, aiming at increased composite mechanical properties. These new developments will be presented in Chapter 5.

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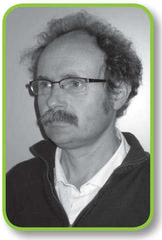
- IV - Matrix polymers



Christophe BALEY,
Professor at the University of Bretagne Sud, LIMATB (laboratory of engineering of materials of Bretagne), France

Peter DAVIES,
Dr. Research Engineer, IFREMER (French Ocean Research Institute) - Materials and Structures group, France

1. Introduction

A composite material can be defined most simply as a two-phase assembly consisting of a matrix and a reinforcement (usually in the form of fibres). In this chapter, it is the matrix which is of interest. There are three families of matrix materials: polymers (plastics), ceramics and metals. For a composite reinforced with natural fibres, the matrix is usually a polymer, so in this chapter only these will be considered.

Polymers are often referred to as plastics, from the Greek adjective "plastikos", meaning "able to be moulded", leading to the noun plastic ("plasticus" in Latin).

The definition of a composite as composed of fibre and matrix is not complete; the interface between these two should also be recognised as an important third phase. It enables loads to be transferred between the matrix and fibres (this will be discussed in more detail below) and guarantees the cohesion of the composite. The quality of this interface has a strong influence on the mechanical properties, and particularly long term durability (the behaviour in wet environments and fatigue performance).

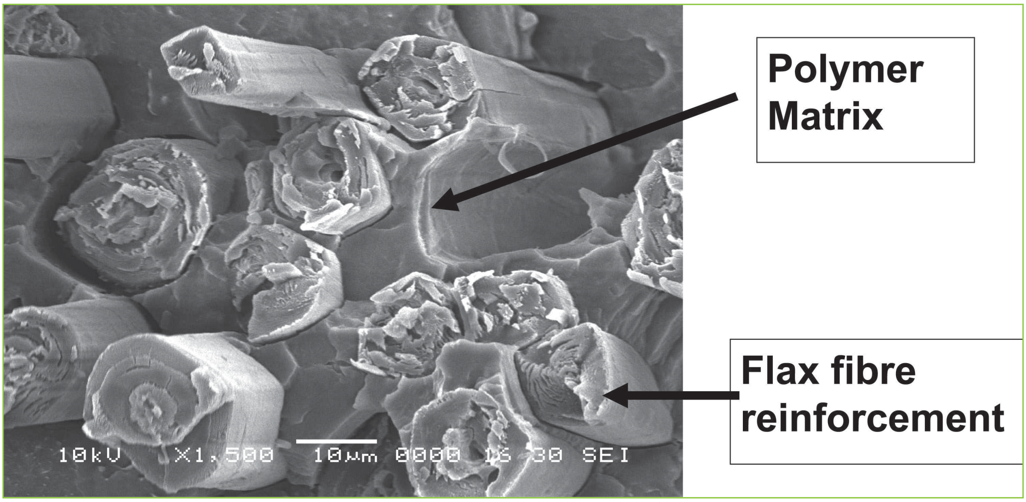


Figure 1: Example of a polymer (plastic) reinforced by flax fibres.

2. Role of the matrix in a composite material

In a composite material, the constituents (fibres, matrix and fibre/matrix interface) each have a role to play. In this paragraph, the role of the matrix will be described.
The fibres bring high mechanical properties, and the role of the matrix is to distribute external loads between the fibres and to protect them. The matrix (polymer) transfers the loads via the fibre/matrix interface, so good adherence is required. The choice of polymer will depend on the requirements of the final component (e.g. service temperature), on the manufacturing process, and on its compatibility with the fibres (wetting, impregnation, viscosity).

To illustrate the influence of the matrix and the fibre/matrix interface on the stiffness and strength of a composite, we can imagine a ply reinforced with only unidirectional fibres loaded in different ways. The ply has two principal directions (L,T), with L longitudinal and T transverse (Figure 2). The ply is assumed to be perfect with no defects.
At low loads applied in the longitudinal fibre direction (L), neither the matrix nor the fibre/matrix interface plays an important role; the response is governed mainly by the fibre volume fraction, and stiffness can be estimated by the "rule of mixture" formulas. The matrix thus contributes very little to the composite stiffness.

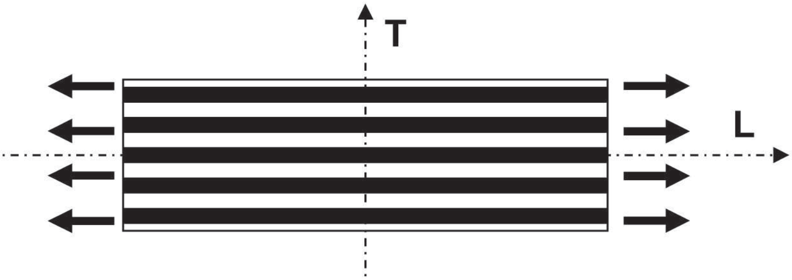


Figure 2: Ply reinforced by unidirectional fibres loaded axially in tension.

As the load increases, because all the fibres do not have exactly the same properties, the weakest fibres will be overloaded and break. In the failure zone, it is the matrix and the interface which ensure that load is transferred to unbroken fibres. Final ply failure will occur after damage of this type accumulates until the section can no longer support the applied load.

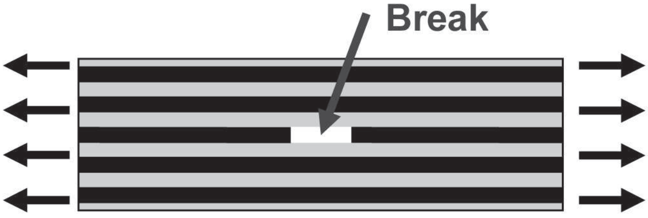
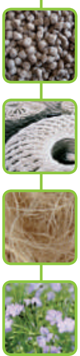


Figure 3: Fibre breakage in a unidirectional ply loaded axially in tension.



When loads are applied in the transverse direction to the fibres, the behaviour is dominated by the matrix and fibre/matrix interface (Figure 4). The matrix polymer contributes to the transverse composite stiffness.

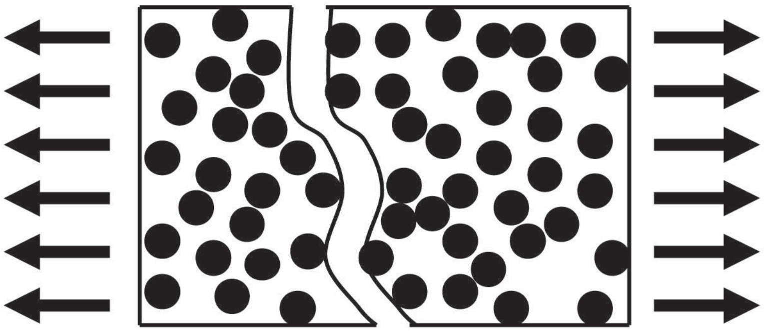


Figure 4: A unidirectional ply under transverse tensile loading.

Under longitudinal compression, the main failure mode is fibre buckling (Figure 5). In this case the matrix is again important, as it restrains the fibres.

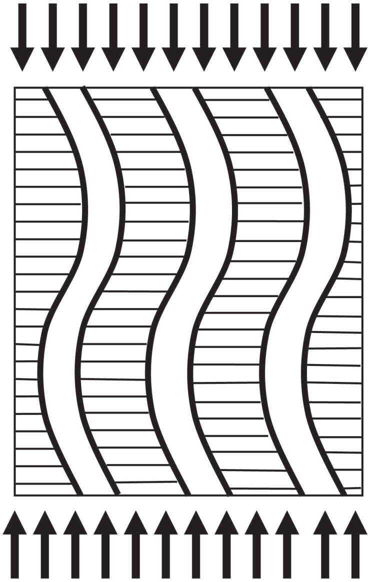


Figure 5: Example of damage development in a unidirectional ply loaded in longitudinal compression.

When the ply is loaded at an angle to the fibres (off-axis) between L and T, it is the shear properties of the matrix and interface which are important (Figure 6).

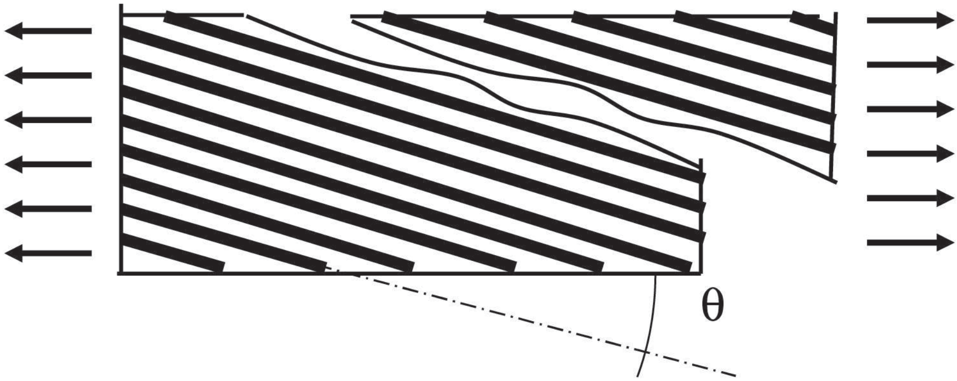


Figure 6: Failure of a unidirectional ply loaded in tension off-axis.

For a composite reinforced by randomly oriented fibres (Figure 7), the behaviour is more complex, but the matrix and interface properties must be adequate to ensure the load transfer in the regions where transverse tension and shear operate.

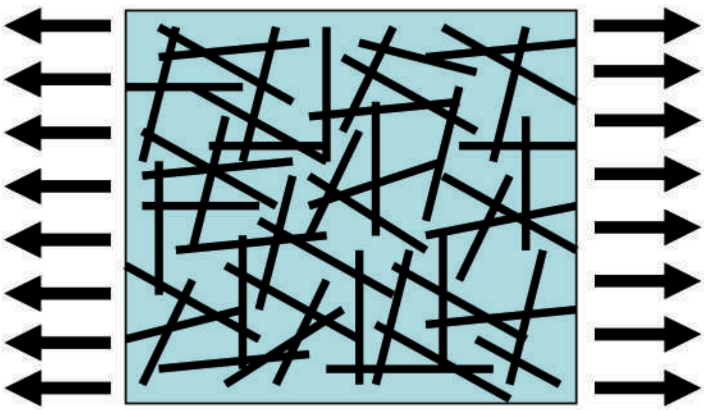


Figure 7: Tensile loading of a composite reinforced by randomly oriented fibres.

These examples underline the importance of the matrix and fibre/matrix interface (the quality of the bonding between fibres and matrix) for the mechanical performance of composite materials.

3. Polymers: what are they?

Polymers (or macromolecules) are very large molecules made up of smaller units, called monomers or repeating units, covalently bonded together (Figure 8).

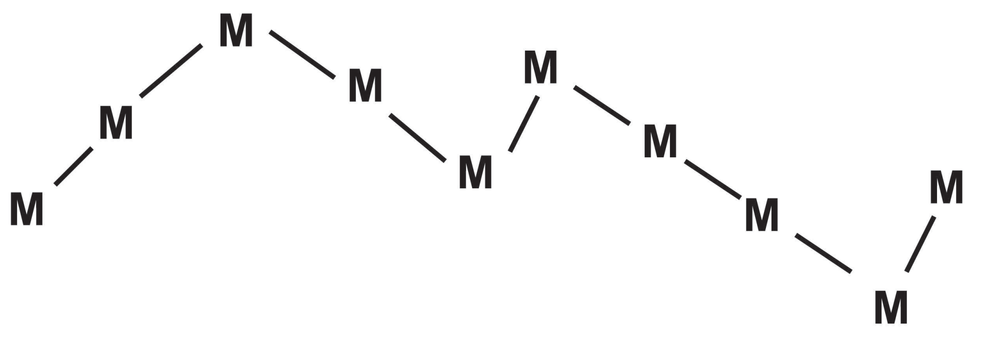


Figure 8: A polymer chain.
M is a monomer unit, -- represents a covalent bond.

This specific chainlike molecular structure of polymeric materials is responsible for their mechanical properties. There are strong covalent bonds along the chains, but weaker secondary bonds between chains result in low stiffness (thermoplastics) unless cross-links can be introduced between chains by chemical reactions (thermosets).

Figure 9 shows the base monomers of polyethylene, a simple, widely used thermoplastic polymer.

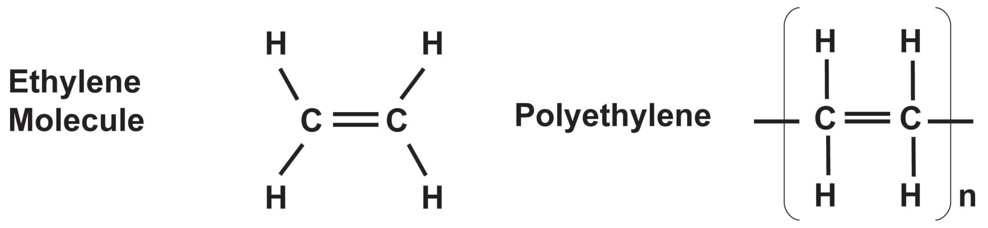


Figure 9: Polyethylene monomers (C carbon, H hydrogen).

Another common polymer is cellulose, the main constituent of plant fibres (Figure 10).

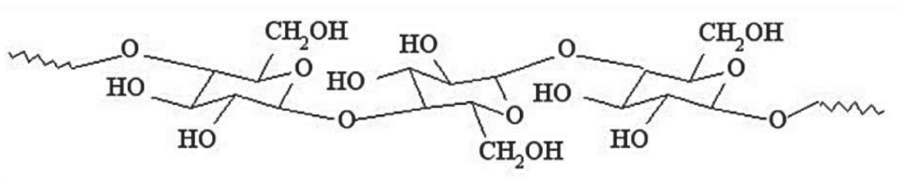


Figure 10: Structure of cellulose, main constituent of plant fibres.

Polymer architecture can vary. In Figure 11, three possible molecule architectures are depicted.

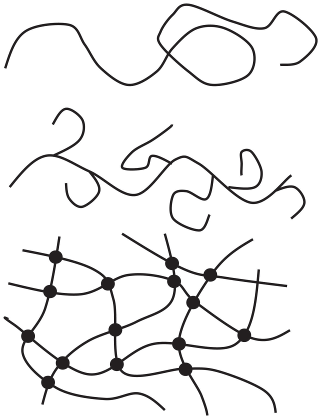


Figure 11: Types of molecular configuration: (a) linear chain, (b) branched molecule, (c) cross-linked network.

A *linear polymer (e.g. polyethylene)* consists of a long chain of monomers. A branched polymer has branches covalently attached to the main chain. *Cross-linked polymers (e.g. epoxy resins)* have monomers of one chain covalently bonded with monomers of another chain. Cross-linking results in a three dimensional network; the whole polymer is a giant macromolecule. *Elastomers*, such as rubber, are loosely cross-linked networks, while *thermosets* are densely cross-linked networks.

Another classification of polymers is based on the chemical type of the monomers:
Homopolymers consist of monomers of the same type; *copolymers* have different repeating units. Furthermore, depending on the arrangement of the types of monomers in the polymer chain, we have the following classification:

- In *random* copolymers two or more different repeating units are distributed randomly.
- *Alternating* copolymers are made of alternating sequences of the different monomers.
- In *block* copolymers, long sequences of a monomer are followed by long sequences of another monomer.
- *Graft* copolymers consist of a chain made from one type of monomers with branches of another type.

Both mechanical properties (stiffness and strength) and physical properties (density, response to temperature changes) of polymeric materials depend on the microscopic arrangement of their molecules. Polymers can have *amorphous* or *semicrystalline* (partially crystalline) structures (Figure 12). Amorphous polymers lack order and are arranged in a random manner, while semicrystalline polymers are partially organised in orderly crystalline structures.

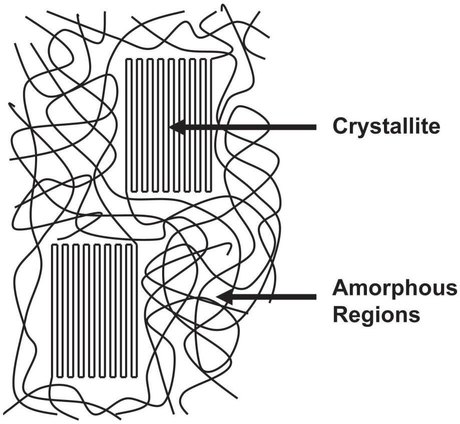


Figure 12: Amorphous and semicrystalline regions in a semi-crystalline polymer.

4. Polymer families: relationships between structure, manufacturing and properties

The mechanical behaviour of polymers is strongly dependent on the temperature. Figure 13 shows an example for an amorphous thermoplastic polymer. At low temperature, this polymer is stiff and brittle (glassy behaviour), while at high temperature it is soft and ductile (rubber-like behaviour). In the central part of the plot (between points A and B) a glass transition temperature can be defined (often referred to as Tg). For semi-crystalline thermoplastic polymers, the slope in the transition region (A-B) is more gradual, as the crystalline regions retain some properties above the Tg of the amorphous part up to the crystal melting temperature Tm.

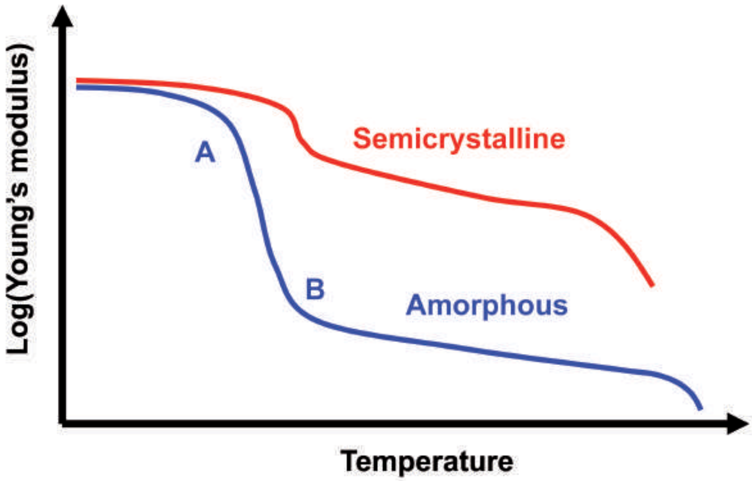


Figure 13: Influence of the temperature on the stiffness of a polymer.

At room temperature, the mechanical behaviour of a polymer in tension depends on its molecular characteristics and its structure (Figure 14). Some polymers are naturally brittle (glass-like), others are very ductile (deform extensively before failure). The difference depends on the conformation of the molecular chains, and their ability to deform before breaking. In many cross-linked (thermoset) polymers the cross-links block the deformation, while in thermoplastics the chain slip can result in high strains at failure.

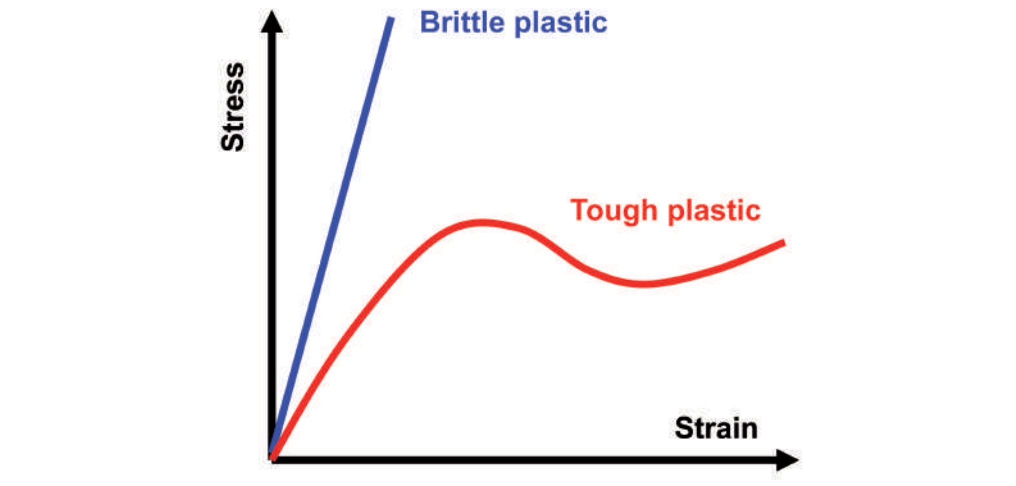


Figure 14: Behaviour of different polymers under tensile loads.

While the initial slope yields the modulus, the area under the curve provides the energy to fracture.

Polymers are often grouped in three categories, according to their architecture:

- Thermoplastics (which may be partially crystalline)
- Thermosets
- Elastomers (which will not be described here, as they are rarely used in composites)

a) Thermoplastic polymers

Thermoplastic polymers consist of molecular chains with strong covalent bonding. These chains are linked together by weak van der Waals and hydrogen bonds. Thermoplastics, as their name suggests, soften when heated. They can be dissolved in certain solvents.
Behaviour of thermoplastics:

- $T < T_g$ (glass transition temperature) – glassy behaviour, brittle. The thermal energy is insufficient to break the large number of weak bonds between neighbouring macromolecular chains;
- $T_g < T < Tm$ (melting temperature) – the behaviour is rubbery. Some weak bonds in the amorphous regions are broken;
- $Tm < T$ (Tm around 1.4 T_g) – viscous flow. The secondary bonds in the crystalline part of the polymer are broken and interlinked molecules can slip past each other. Loss of original shape; thermoplastics can be formed in this temperature range.

Examples of thermoplastic polymers: polyethylene, polypropylene, polyamide (nylon).

In the melted state, the structure resembles a plate of spaghetti (Figure 11). On cooling, this spaghetti may solidify without rearrangement: the polymer is then amorphous. But some polymer molecules can re-arrange and the chains can align during cooling to form crystalline zones. The polymer is then described as semi-crystalline.

b) Thermosetting resins

Thermosetting resins are composed of molecular chains linked by strong covalent bonds to form a three-dimensional network that is insoluble and does not melt before degrading when heated. Behaviour of thermosets:

- $T < T_g$ – glassy behaviour due to the many primary bonds (3D structure) between molecules;
- $T_g < T$ – rubbery behaviour as bonds break progressively, but some cross-links remain.

Thermosets do not melt due to the strong cross-linking bonds between molecules. There is no viscous flow, only degradation at high temperature.
Thermosets are amorphous.
Examples of thermosets: epoxy, vinyl ester, phenolic. Tg is typically in the 50-150°C range for these materials.

Elastomers
These are polymers with high molecular weight and a small number of cross-links between chains (1% of the monomers are linked).

- $T < T_g$ – glassy behaviour;
- $T_g < T$ – rubbery behaviour. The small number of cross-links allows large elongations without rupture (1000%). For elastomers, the Tg is below room temperature.

Note: It is very rare to use any of these three types of polymer in their pure form. Additives are always present in order to improve physical or chemical properties or to improve processing. These include pigments, plasticisers, stabilisers and lubricants, which together may represent more than 50% of the final weight for an elastomer.

Manufacturing
Before manufacturing, the polymer may be in different forms. A thermoset matrix is generally liquid, while thermoplastics are solid. For the latter, and depending on the process, the form may be pellets, powder, film or fibres.
The processing cycle will depend on the nature of the polymer, the main parameters are the temperature, time and pressure. Figure 15 shows a composite processing cycle for a composite with a thermoplastic matrix, while Figure 16 shows the manufacturing cycle for a thermoset matrix composite.
To impregnate fibres with a **thermoplastic**, it is necessary to reduce the polymer viscosity so it can flow between the fibres. This requires high temperature and pressure (see Chapter 6). In order to improve the impregnation, the flow distance of the molten thermoplastic can be reduced by intimately pre-mixing the reinforcing fibres with thermoplastic powders of fibres.
Thermosetting polymers have low viscosity when they are not yet cross-linked (also called "cured"), and hence consist of only small molecules. Uncured thermosets can impregnate the fibres more easily, in many cases (polyester, vinylester) heating is only required to activate the chemical cross-linking reaction, which solidifies the polymer. Some epoxy formulations are also available in liquid form, though heating may be needed to reduce their viscosity. An alternative approach is to supply pre-impregnated fibres, with the epoxy already partially cured, heating and pressure (vacuum) are then needed to complete impregnation and cure.

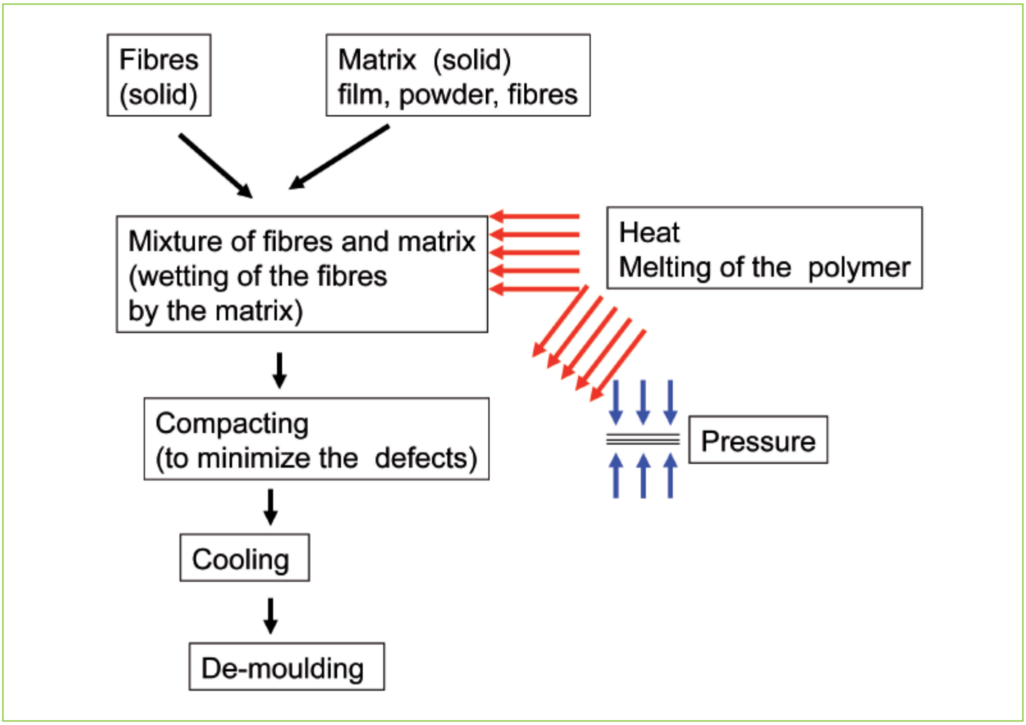


Figure 15: Forming cycle of a composite with a thermoplastic matrix.

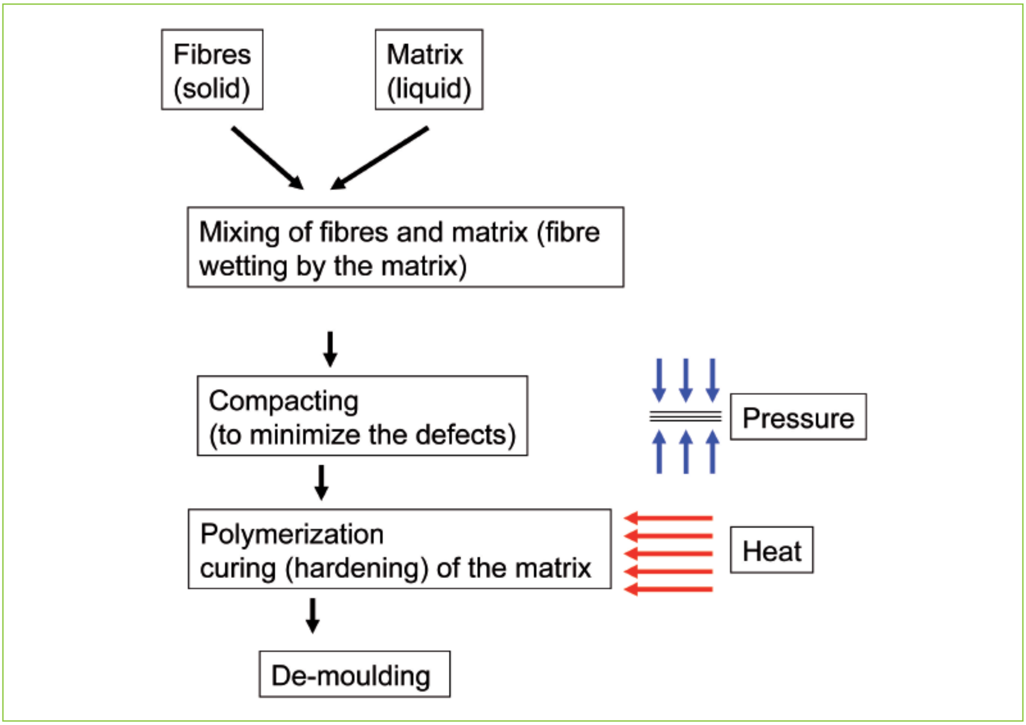


Figure 16: Forming cycle of a composite with a thermosetting matrix.

5. Examples of polymers reinforced with natural fibres

The majority of the polymers in use today (PE, PP, PA, epoxy, etc.) are petroleum based. There are many naturally occurring macromolecular substances, however (Table 1). The main ones are:

- fibrous proteins such as fibroin of silk, keratins (hairs, wool, feathers and nails);
- cellulose in plant cell walls (plant fibres such as flax and hemp) and starch in plant cells;
- rubber.




- Table 1 -
Some natural polymers.

Name	Source	Application
Cellulose	Wood, flax, hemp	Paper, clothing
Starch	Potatoes, corn	Food, thickener
Wool	Sheep	Clothing
Silk	Silk worm	Clothing
Natural rubber	Rubber tree	Tires
Pitch	Oil deposits	Coating, roads

Table 2 shows typical properties of different types of polymer.

- Table 2 -
Properties of different polymers. TP = thermoplastic / TS = thermoset

Polymer	Density (g/cm^3)	Young's modulus (GPa)	Tensile strength (MPa)	Failure strain (%)	Tg (K)	Tm (K)	Family
PE (HD)	0.95-0.97	0.55-1,10	20-37	10-1200	270	390	TP
PP	0.90-0.91	1.20-1.70	30-70	10-600	253	245	TP
PVC	1.30-1.60	2.40-4.10	40-60	40-80	350	430	TP
Polyester (Thermoset)	1.10-1.40	1.30-4.50	45-85	1-5	340	-	TS
Epoxy	1-2-1.40	2.10-5.50	40-85	2-7	380	-	TS
PLA	1.21	3.3	30	2.5	310-340	400-450	TP Bio
PHB	1.18	3.5	40	5-8	275	410-450	TP Bio

In order to limit environmental impacts, or to produce polymers from renewable resources, or manage end-of-life disposal by composting (biodegradable polymers), various formulations have been developed. These are biopolymers, or bioplastics, and are essential products to develop a sustainable plastics industry. They reduce the dependence on fossil fuels and, in some cases, are easily biodegradable.

The PLA and PHB in Table 2 are biopolymers, in comparison to the other synthetic polymers. They are produced from starch and sugar. Their stiffness and strengths are similar to those of traditional polymers but failure strains are significantly lower.

Biopolymers

Within the biopolymers there are different types (depending on the source) and end of life behaviour.

Table 3 summarises these and shows different types of biopolymers, compared to fossil fuel sourced polymers.

- Table 3 -
Different types of biopolymers.

	Natural polymers:	*Bio-based polymers (renewable feedstock, synthesised):*	*Synthetic petroleum-based polymers*
Biodegradable	Lignin	PLA PHA, PHB Starch	PBS PCL PVA
Non-biodegradable	Cashew nut shell resin (CSNL)	Furan resin Vegetable oil -PUR (polyol) Ethanol-based PE Some nylons (PA-11)	Most well-known polymers: PP, PE, nylons, etc. Epoxy, Polyester

There are at least three factors that define how environment-friendly a material is:
* renewability: how quickly are the ingredients that go into making the plastic created in the environment?
* degradability: how quickly can the plastic be re-integrated into the environment after it is no longer being used?
* production: how much pollution or waste is created during the process of actually making the plastic?

Traditional plastics (synthetic, non-biodegradable, see bottom-right corner of Table 3) fail on all three of these points. However, the choice of biopolymer matrix for a particular composite application will depend on many parameters. These include mechanical properties, manufacturing considerations and cost. For example:

- There are few biopolymer matrix materials with adequate mechanical properties to replace the thermoset polyester in GRP (glass reinforced plastic).

- Some thermoplastic PLAs have good mechanical properties but economic manufacturing methods must then be developed to replace the hand lay-up/wet impregnation used for GRP.
- Thermoplastics require moulds that resist temperatures of 150°C or more, so these require an investment which can only be economically justified provided the quantity of components is high enough.

Even these simple examples show that direct replacement of existing materials with more environment-friendly materials requires a global approach, integrating life cycle analysis in order to quantify global benefits. More details are given in Chapter 9.

There are few commercially available natural fibre/biopolymer products today. Flax/epoxy is supplied as a pre-impregnated material, and some short natural fibre reinforced thermoplastics are available. Small quantities of commingled flax/PLA can also be obtained. This aspect is discussed in more detail in Chapter 5.

The development of biopolymers is part of an eco-design strategy. Eco-design involves the systematic integration of environmental considerations during the design of a product or process. In order to evaluate the environmental impacts, a life cycle analysis (LCA) must be performed. These are described elsewhere in this book (Chapter 9).

Biodegradable polymers

Biodegradable biopolymers are made from natural polymers (naturally biodegradable), or from synthetic polymers that can be degraded by micro-organisms, or by a mixture of these two families.

Among the biodegradable biopolymers there are polymers which are:

- microbial: these are secreted by micro-organisms after fermentation of natural raw materials (glucose, sucrose from fatty acids), the best known are PHA (polyhydroxyalkanoate) and PHB (polyhydroxybutyrate). These are thermoplastic polyesters. The PHAs were first identified in 1925 and are finding applications in packaging and medical implants. There are many different grades, and they can be manufactured with traditional equipment. The PHBs have similar properties to PP. They are often used in co-polymers (PHB/PHV) and various commercial grades are available (*Biomer*, *Biopol*, *Nodax*);
- vegetable: the best known are starch, cellulose and lignin. These are polysaccharides, and various commercial products are available such as *Vēgēmat* (from corn), *Sipol* from potato flour, *Mater-Bi* from starch with natural plasticisers, *Cellophane* from cellulose, and *Arboform* from lignin mixed with flax and hemp;
- animal: chitin, for example, which is found in the shells of shellfish and insects;
- protein: silk, collagen and gelatine, gluten and wool;
- chemical: by polymerisation of biological products such as lactic acid. Lactic acid is produced by the fermentation of sugars (beetroot, potatoes, maize) but may also be made chemically. Commercial PLAs include *Lacea*, *Eco-Pla*, *Lacty* and *Solanyl*;
- synthetic: including bonds which can be hydrolysed (such as esters or amides) as in aliphatic polyesters such as poly(glucolic acid), the PLA's poly(lactic acid) and polycaprolactone.

It is important to recycle these materials as much as possible. Only thermoplastic polymers allow recycling (grinding, then heating and forming new products).

6. Aging and long-term performance

The long-term behaviour of composite materials depends on the stability of the matrix, the fibre/matrix interface and the fibres. The role of the matrix is very important and will depend on additives (stabilisers, anti-oxidants, mineral fillers) on the purity of the polymer, and the molecular weight of the monomers. For thermosets, the quality of the monomer and hardener and the degree of cross-linking are important. For thermoplastics, the degree of crystallinity and the morphology will affect the behaviour. The fibre type, sizing (fibre coating) and orientations will also play a role.
Aging can act on the constituents individually, but also on their interfaces; degradation often initiates in the fibre/matrix interface region.

Aging mechanisms for polymer matrix composites differ according to the type of polymer and the aging conditions (temperature, humidity, oxygen pressure), but they also depend on the processing history (cure cycle, cooling rate, internal stresses) and processing route (injection, contact, resin transfer moulding, etc.), and on the component structure (geometry).

Two types of aging can be distinguished:

- physical aging, which covers phenomena for which the chemical structure of the macromolecules is not modified. It includes aging caused by mechanical loads, relaxation phenomena and mass transfer effects caused by heat transfer, absorption and molecular diffusion;
- chemical aging implies a chemical modification to the material. This includes thermo-chemical aging, thermal oxidation, photochemical oxidation, radio-chemical, biochemical and biological effects and aging due to chemical agents. These effects are often added to physical aging effects and may interact.

For example, we can compare the behaviour of a traditional thermoset polyester used in many industrial composite applications with that of a PLA biopolymer. On long-term exposure to water, both will degrade by hydrolysis (polymer chain breakage). This is a chemical aging mechanism that results in the loss of mechanical properties, reduced strength and strain to failure. Under the same aging conditions, the degradation of the biopolymer will be more rapid than that of most thermoset polyesters, so aging requires particular attention in design with these materials.

The lifetime of a material is defined as the time over which the material can perform its main functions without repair. In order to determine this lifetime, both in-service experience and accelerated tests are used.

7. End-of-life recycling, incineration or biodegradation

A detailed discussion of the life cycle of polymers, recycling and end-of-life behaviour is given in Chapter 10.

Recycling

Recycling is one of the parts of a waste treatment strategy known as “the three R’s”:

- Reduce – actions aiming to reduce the quantity of products (packaging for example) that finish as waste products;
- Re-use – actions aiming to re-use products to give them a new life, either as the same or for a different application;

- Recycle – includes operations to collect and treat waste in order to return the materials to the manufacturing cycle.

Recycling has two main ecological effects:
- reduction of the volume of waste, and thus of the pollution that it causes (certain materials can take decades or even centuries to degrade);
- conservation of natural resources, since recycled materials replace the extraction of new raw materials.

Recycling can significantly help to reduce the quantities of waste to store or incinerate, but is not sufficient today to stop the increase in waste production.

Biodegradation

Biodegradation is the decomposition of organic materials by micro-organisms such as bacteria, fungi or algae. **Biodegradability** is the property of a biodegradable substance. It can be evaluated in terms of the degree of decomposition of a substance and the time necessary to achieve this decomposition. There are polymers which are biodegradable under industrial compost conditions. These are described as biocompostable polymers. Industrial composting takes place under controlled temperature and humidity conditions; it requires special equipment, e.g. to grind, compact, air, turn and then sift.

Incineration

This consists of burning waste in ovens at temperatures between 700°C and 900°C.
This process transforms the waste into volatiles and ash. Polluting emissions are limited and controlled. The incineration of certain plastics is a source of dioxins (dangerous chemicals which are very stable and hard to degrade). Incineration is an alternative to dumping however, as not everything can be recycled. Separation and purification processes are not always available or economic.

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- V - Semi-products with flax and hemp fibres

Joris Baets,
Postdoctoral Researcher at the Department Metallurgy and Materials Engineering,
KU Leuven, Belgium
Coordinator of the European Scientific Committee of CELC

For the manufacturing of composites, the fibres and the matrix have to be mixed during production. As described earlier (Chapters 3 and 7) the fibre orientation is very important for the resulting properties. Therefore, semi-products have been developed in which the fibres are already oriented as needed for the final composites.

There are two groups of semi-products: the dry (preforms) and the "wet" (prepregs):

- The dry preforms consist only of the fibres, the matrix will be added during production of the composite.
- In the prepregs, the fibres are already pre-impregnated with the matrix. During manufacturing, the impregnation is completed and the matrix consolidated.

These two main groups can be subdivided in more groups, as shown in Figure 1.

For synthetic fibres, a large range of semi-products is already available in both groups.

In recent years the flax and hemp industry has developed semi-products adapted to composites. There is now a semi-product available for every type existing in the group of the synthetic fibres.
The different semi-products available with flax and hemp are described hereunder (Figure 1).

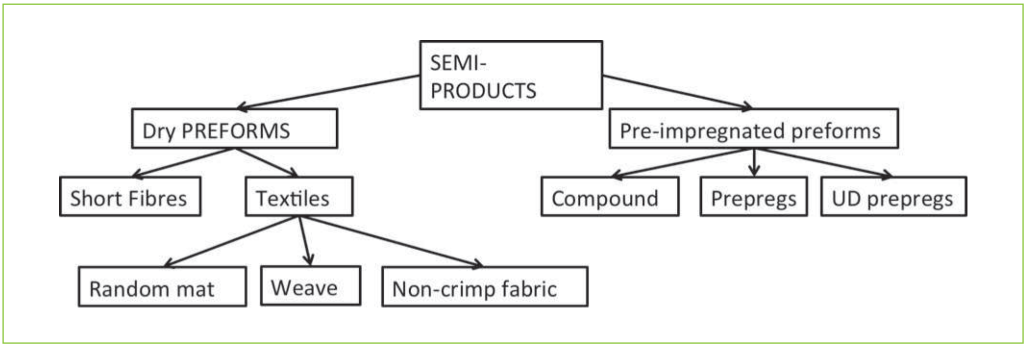


Figure 1: Different types of semi-products: dry and pre-impregnated preforms.

The traditional flax fibre extraction process is completely oriented towards textiles, where the yarns produced need to be very fine, strong and stable. For the production of semi-products for composites, the process is changed. In Figure 2, the traditional process is shown in black. Nowadays the products from earlier on in the extraction and refining process are also used to produce semi-products, as shown in red. These "upstream" preforms are cheaper and have better mechanical properties, because of less handling and lower twist. Some of these new product lines are already available, others are in development.

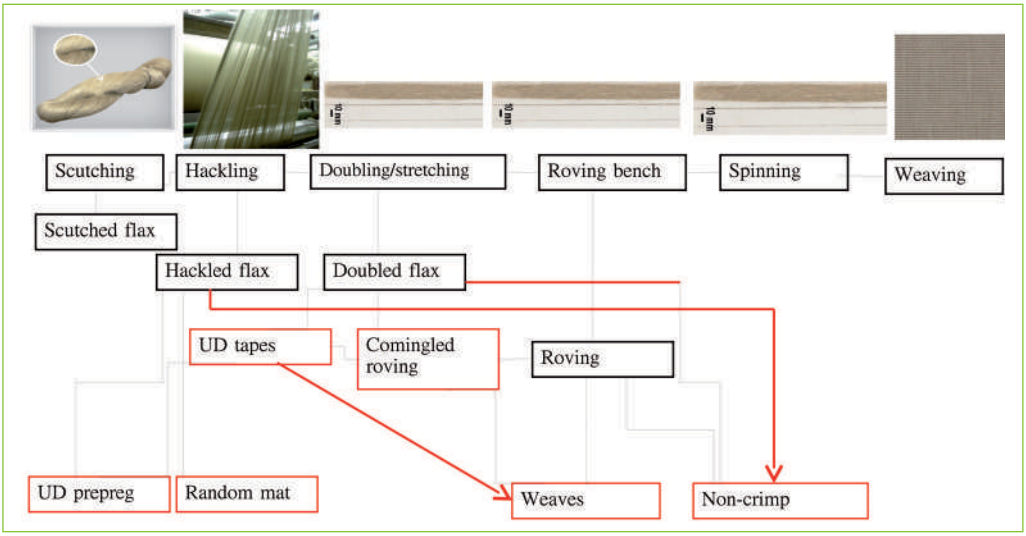


Figure 2: Preforms developed by the European flax industry.

Preforms

Preforms can be divided in two main groups: 1) short (loose) fibres and 2) textiles. In the latter, the fibres are fixed in a textile structure, and therefore the orientation of the fibres in these preforms is the orientation of the fibres in the composite. In the former, the fibres are loose before manufacturing of the composites, and therefore the orientation is dependent on the process. However, this will always lead to a random distribution.

Short fibres

The simplest preform is just a bunch of fibres, especially short fibres (< 150 mm). The short fibres (Fig. 3) are cut fibres (mostly from a continuous sliver) that can be added during manufacturing to a polymer to reinforce it. Short fibres can be used in extrusion or injection moulding. However, due to the lightness of the natural fibres, the feed process is more difficult than with the heavier glass fibres, so it is easier to use a compound (see further down). Another possibility is to use these fibres for making random mats.

The short fibres are available in different lengths and different purities. The purity depends on the amount of shives still present in between the short fibres.

There is a whole range of products already available. The length of the fibres can vary between 1 and 150 mm, and purities of 95 to 99% are available for both flax and hemp fibres. These fibres are produced by cutting to the desired length. The mechanical properties of these fibres are of course the same as the values mentioned in Chapter 2 because the fibres have not been treated.

Figure 3: Short fibres of flax 10 mm (left) and hemp 3 mm (right). ***(Source: FRD)***

When the original fibres are not cut but crushed up to a very short length, the result is more like a powder (Fig. 4). This powder can be used as a filler material that also has a reinforcing effect, in extrusion and injection moulding. The reinforcing effect is lower, although it is easier to produce complicated shapes with this powder than with short fibres. The length can vary between 0.15 and 2 mm.

Figure 4: Very short crushed fibres, which are powder-like. ***(Source: FRD)***

All short flax and hemp fibres have the same problem with temperature, as they cannot resist temperatures that are too high. These short fibres should be processed at a temperature lower than 200°C, otherwise a degradation of the properties will occur. Hence, when they are used as reinforcement for thermoplastics, the melting temperature of the thermoplastic should not be too high.

Random mats

The group of textile preforms can be subdivided in oriented and non-oriented textiles. The non-oriented preforms or random mats are the simplest preform, cheap to produce, but they lead to composites with lower mechanical properties than with the oriented textiles. In a random mat, the fibres are entangled, which gives enough strength to the textile for manipulating and draping.

The fibres used are normally the by-products from scutching and hackling, the so-called short fibres (see Fig. 2).
Because of the production technique, there can be more fibres oriented in the machine direction, so that the distribution of the fibres is not perfectly random anymore. Hence, such 'random' mat composites will be stiffer and stronger in the machine direction.

The random mats can be used in liquid moulding, like RTM and vacuum infusion. The areal densities of these mats can vary between 400 and 2,400 g/m² when they are made by needlepunching (the fibres are intertwined by the use of needles), while with the spunlace technique (the fibres are intertwined with water jets), the densities can go even lower (Fig. 5).

When a random mat of flax or hemp fibres is made for use in thermoplastic matrix composites, this is often done with a mixture of both reinforcing and thermoplastic fibres (Fig. 6). Because the reinforcing fibres and the matrix are already mixed in this material, the production and shaping of the composite can go very fast: heating up the mixed random mat above the melting point of the thermoplastic and shaping it by a cold press. Because of the high production rate, this type of preform is used a lot in the automotive industry. The aerial densities of these products are in the same range as in the pure random mats (400 and 2,400 g/m²). The mechanical properties of the material are limited (strength up to 50 MPa and stiffness of around 5 GPa), but because of the light density of 1 kg/dm³, the material can be made thicker to reach the required mechanical properties.

Figure 5: Non-woven flax mat produced by needlepunching. *(Source: ECOTECHNILIN)*

Figure 6: Mixed non-woven flax/PP mat. *(Source: ECOTECHNILIN)*

Low-twist yarns

Traditional flax and hemp yarns have a high twist because this leads to very fine, strong and stable yarns, as requested by the textile industry for weaving and knitting. This is opposite to what is needed for high performance composites, for which a low twist is essential (see Chapter 3). A lower twist decreases the strength of the yarn, which is a disadvantage when the yarn is

(Source: *SAFILIN*)

used in a textile technique. A solution can be found in a low-twist yarn or roving of flax or hemp fibres, which is the result of the production step just before spinning (see Fig. 2). In this product the twist is several times lower than in a normal (textile oriented) yarn, 40 twists per meter compared to normally around 280 twists/m. This leads to about a 20% increase in the composite mechanical properties compared to composites with traditional yarns, and the dry product is still strong enough to make the production of composites possible.

When the stiffness of composites made with these low-twist rovings is back-calculated into the stiffness of the rovings (using the formulas presented in Chapter 7), a very high value is obtained: namely a stiffness of 52 GPa. If we further back-calculate, taking into account the fibre twist, a fibre stiffness of 65 GPa is obtained. Following the same back-calculation procedures, a fibre strength of more than 700 MPa has been obtained. This stiffness is almost equal to that of glass fibres, but because of the lighter density (1.45 compared to 2.54 g/cm³), a higher specific stiffness is obtained. This better specific property can of course be transferred to the composites made with these rovings.

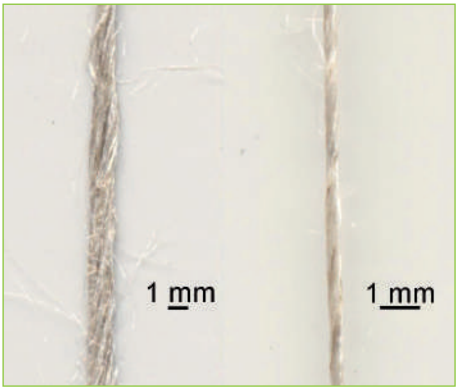


Figure 7: Picture of a low-twist flax roving (left) and a traditional flax yarn (right).

Weaves

In the group of oriented textiles, the most basic is a weave. A woven fabric consists of interlaced yarns in 2 directions. One direction is the machine direction and is called the warp-direction, while the weft-direction is perpendicular to it. Different weave patterns can be made, leading to different properties on a mechanical level but also on the stability of the orientation and the drapability (see Chapter 3). However, because of the technique, the orientation of yarns in the weave is always 0 and 90°. The properties of the weaves (and their composites) also depend on the linear density of the yarns used, which can be different in both directions. Another important parameter is the amount of warp and weft yarns per unit of length. This last parameter is not necessarily equal for both directions, which can lead to unbalanced weaves.

Until now, most weaves have been produced with traditional textile yarns, having a high twist. However, ongoing developments include weaving with rovings and even UD-tapes. These weaves will have better properties because of the reduced twist of the rovings (Fig. 8).

For flax fibres, there are mainly two types of weaves, the balanced weaves and the UD-weaves. The properties of both are largely different because of the fibre architecture. With the UD-weaves, with up to 95% of the fibres in warp direction, a stiffness in the warp direction of 21 GPa can be reached with a fibre volume fraction of only 33%. In this case, the strength is equal to 221 MPa. For balanced weaves with the same fraction of fibres, the stiffness and strength (in warp and weft direction) are equal to 9.9 GPa resp. 110 MPa.

(Source: *Libeco Lagae*) (Source: *Groupe Depestele*) (Source: *Dehondt Groupe*)

Figure 8: Different flax weaves.

In the case of flax fibres, a treatment for better adhesion and lower moisture absorption can be useful. This treatment, which is already available on different weaves, reduces the moisture absorption to lower than 2%. The mechanical properties of a composite with these weaves are excellent: for a fibre volume fraction of 36% a stiffness of 21 GPa in warp direction is reached with a UD weave (with at least 95% fibres in warp direction), while the strength is 261 MPa.

Non-crimp

A non-crimp fabrics consist of different layers of fibres – each layer with its own direction –, which are stitched together (see Chapter 3). The important parameters of a non-crimp fabric are the number of layers and the direction of the layers, as well as the areal density of each layer (Fig. 9). The advantage of a non-crimp fabric is that the different layers are straight (or flat) and therefore have no crimp. The orientation of the different layers can go from 20° to 90°, with a positive or negative angle relative to the machine direction. When 0° layers are used, they have to be placed in the outside layers, because of the production technique. At the moment, only ± 45° non-crimp fabrics exist in flax and hemp, but developments are ongoing for other orientations.

Figure 9: Flax fibre non-crimp fabrics (+/- 45°). (*Source: CRST*)

Pre-impregnated preforms

In prepregs the fibres are already mixed with the matrix before the final manufacturing of the composite. The difference with composites is that the impregnation is not yet optimal, the curing reaction for thermosets is not yet complete, and the shaping still has to be done.

Compound

A "prepreg" of short fibres is called a compound. These are pellets of a thermoplastic in which short fibres are mixed. The short fibres are fed to a molten thermoplastic in an extrusion line, where a rotating screw mixes the fibres with the thermoplastic. The high shear forces reduce the length of the fibres. The mixing process is made more difficult by the low density of flax and hemp fibres compared to glass fibres, so special feeding units are necessary.

There are different compounds available, with different matrix materials and different volume percentages of fibres (Fig. 10).

	PP	PVC	PA	PLA	ABS	PE
Flax	X	X		X	X	
Hemp	X	X			X	X

Of course, the large range of combinations also gives a large range in properties. With a PVC or ABS matrix a stiffness up to 7 GPa can be obtained, with a strength of 60MPa. For a matrix with a lower stiffness like PP, the stiffness and strength values are around 4 GPa and 40 MPa.

Figure 10: Hemp compound (*Source: AFT Plasturgie*) **and Flax/PLA compound** (*Source: GROUPE DEPESTELE*).

Nowadays recycling is a hot topic. One of the techniques of recycling a thermoplastic composite is to grind it down and to re-compound it into pellets, which can then be used in injection moulding or extrusion. An interesting example is the recycling of production waste of flax fibre random mat thermoplastic prepregs. The resulting product is a compound with 50 vol% of flax fibres and a PP matrix. (Fig. 11) This can be coloured afterwards, leading to a nice surface effect. The mechanical properties of this material are much higher than for pure PP. The stiffness of this material goes up to 4GPa with a strength of 60 MPa, while the density of 1.15 g/cm³ remains very low.

Figure 11: Compound of recycled flax and PP. (*Source: ECOTECHNILIN*)

Prepregs

The matrix material can also be added to a textile. There are different methods to do this, depending on the type of matrix (thermoset or thermoplastic). In the different methods, the goal is to make a good mixture of fibres and matrix before the composite manufacturing step. This makes the impregnation, and therefore the production, easier and less time consuming. The two techniques used most are:

- Use of a mixed yarn (mainly thermoplastic)
- Pre-impregnation of the textile (mainly thermoset)

Thermoplastic prepregs

The first technique is used especially with thermoplastic matrices. Filaments of the matrix materials are mixed with the yarns. With these mixed yarns the textiles are produced. There are different methods to produce the mixed yarns, two of which are used with flax and hemp fibres:

- co-wrapping, where a filament of the matrix material is wrapped around a yarn of the reinforcing fibre;
- commingling, where the reinforcing fibres are mixed with the thermoplastic filaments during the doubling process. Afterwards a yarn is spun, in which the reinforcing fibres and matrix filaments are mixed more intimately than with the co-wrapping technique.

Combinations of both techniques are also possible and are currently still in development. The goal is to increase the dry strength of the mixed rovings while the properties in the composite are increasing.

There are weaves of mixed rovings with PP and PLA, both using flax as reinforcement. Both UD and balanced weaves are available. The properties of the balanced weave with PLA are much better than with PP. The stiffness is 13 GPa for PLA, compared to 8 GPa with PP, while the strength is 100 MPa vs. 60 MPa, both for a fibre volume fraction of 35%.

Another technique for thermoplastic prepregs is to make use of a thermoplastic powder, which is spread on the weave: under heat, it melts and sticks to the fibres (Fig. 12). This technique is used with PA11, a 100% bio-based polymer. The stiffness of a balanced weave with PA 11 produced with this technique is around 15 GPa for a fibre volume fraction of 60%.

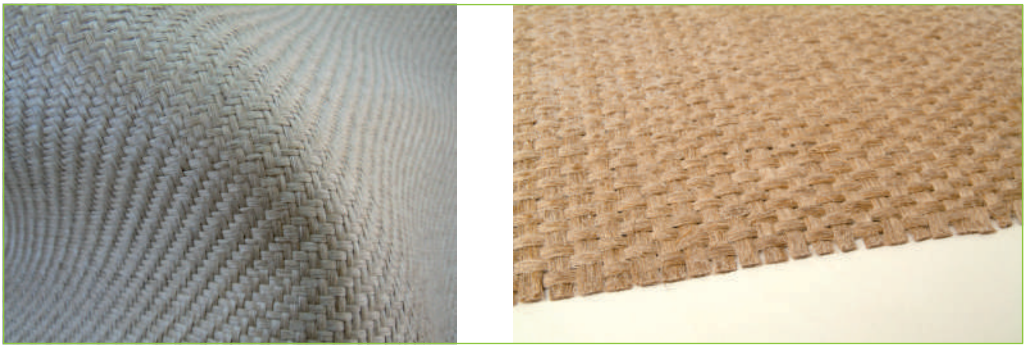


Figure 12: Commingled weave of flax with thermoplastic matrix (left) - (Source: *Groupe Depestele*); Thermoplastic prepreg of flax weave with powder (right) - (Source: *Dehondt Groupe*).

For composites, the best mechanical properties are obtained by using completely unidirectional layers. Because flax and hemp fibres already have some twist, this is not possible with flax or hemp yarns and rovings. One solution is to use untwisted doubled or hackled flax. The problem here is that the continuous ribbons are very weak due to the lack of twist, and the limited strength makes handling very difficult. This can be solved by applying a molten polymer directly on the material, or to calendar a polymer film on the UD-fibre layer. The polymer solidifies and makes the material stronger. The final product is a unidirectional layer of flax with a polymer layer placed on one side and partially impregnating into the flax layer.

The mechanical properties of the UD flax prepreg are high, because of the complete absence of twist and crimp. For a cross-ply laminate of UD layers and PP-matrix, this gives a stiffness of more than 10 GPa for a fibre volume fraction of 35%. For this composite the strength is 130 MPa and the density is 1.05 g/cm³.

Figure 13: UD flax/PP prepreg. (*Source: PROCOTEX Corporation*)

Thermoset prepregs

A prepreg of a flax fibre weave with a thermoset matrix is produced using a hot-melt process. A thermoset (resin + hardener) is spread over the weave and low pressure is applied, leading to very limited impregnation. Afterwards, the prepreg is cooled down to stop the curing reaction. The prepreg process is completely automated. During manufacturing of the composite, the impregnation is completed and the consolidation takes place.

A range of weaves is used for making prepregs. UD weaves as well as balanced weaves are available, while the areal weight varies between 170 and 550g/m². For the UD weaves (with up to 95% of the fibres in the warp direction), the stiffness can go up to 35 GPa in the warp direction with a strength of 330MPa, when the fibre volume fraction reaches 60%. In the case of balanced weaves (Fig. 13), the stiffness is lower. With a fibre volume fraction of 46%, only 11 GPa is reached, due to the use of rather highly twisted yarns.

An important ongoing development is the production of UD thermoset prepregs . A possible solution is to use an epoxy-based preform binder, which gives enough strength to the UD preform to allow manipulating the preform before production. This semi-product can be used as a textile in RTM production or processed further into a complete prepreg.

Figure 13: a prepreg of a balanced flax weave (***Source: LINEO***)

Conclusion

In recent years, the European flax and hemp industry has been developing a wide variety of preforms, specifically for the composites industry. Both dry preforms and prepregs are available nowadays with optimised fibre architectures in order to reach the best possible composite properties.

In this chapter, a systematic overview has been presented of the available dry preforms and prepregs, realised at different stages of the flax and hemp fibre extraction and refining process (see fig. 2). For each of these preforms, some mechanical properties have been given throughout the text. As some of these preforms are still in a development stage, the up-to-now realised mechanical properties are not yet optimal. In Figure 14, a **schematic** overview is given for the **potential** stiffness and strength properties of these different preforms (*these potential properties are based on experimental data and on model calculations, as explained in Chapters 3 and 7*).

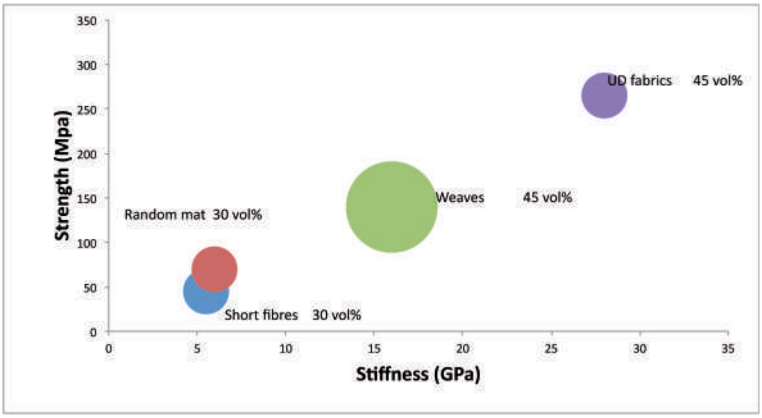


Figure 14: Overview of the stiffness and strength for different types of preforms. The theoretically achievable properties are mentioned. The values for UD fabric are in fibre direction, while the values for weaves are the properties for warp as well as weft direction.

Summary of existing preforms with flax and hemp fibres

Type of preform	Matrix	Vf	Stiffness (GPa)	Strength (MPa)
short flax fibres	PP	30	3,1	22,5
short hemp fibres	PP	30	4	44
flax random mat	PP	30	5	50
flax balanced weaves	epoxy	33	9,9	110
flax balanced weaves	PA 11	60	15	200
flax UD-weaves	epoxy	33	21	221
flax UD weave prepreg	epoxy	60	35	330
flax balanced weave prepreg	epoxy	46	11	113
flax commingled balanced weave	PLA	35	13	100
Low twist roving	epoxy	48	26	377

The European Scientific Committee within the CELC is developing a set of datasheets (with unified lay-out and contents), presenting the main characteristics and composite mechanical properties of the commercially available flax and hemp fibre preforms and prepregs.

For Healthier semi products:

- Lower environmental impact
- Local, renewable resource
- Low abrasion
- No skin irritation when handled
- End-of-life optimization of components
- Recycling by incineration (energy)
- No residue after incineration
- Carbon neutrality
- 100% bio-degradable when combined with an organic matrix

More information about the flax & hemp preforms and their data-sheets is available on: technical@mastersoflinen.com

- VI - Production techniques for natural fibre polymer composites

Gerhard ZIEGMANN,
Prof. Dr. Eng. at the Institute for Polymer Materials and Plastics Processing, Clausthal University of Technology, Germany

Ahmed ELSABBAGH,
Dr. Ing. at the Institute for Polymer Materials and Plastics Processing, Clausthal University of Technology, Germany

The way natural fibres are introduced as reinforcing material in polymer composites has to be adapted to the available production techniques. Figure 1 illustrates the techniques mainly used nowadays for producing natural-fibre polymer composites. The classification in Figure 1 is based on the polymer type (thermoplastic or thermosetting), the status of the products after processing (semi- or finished product) and the post-processing fibre geometry.

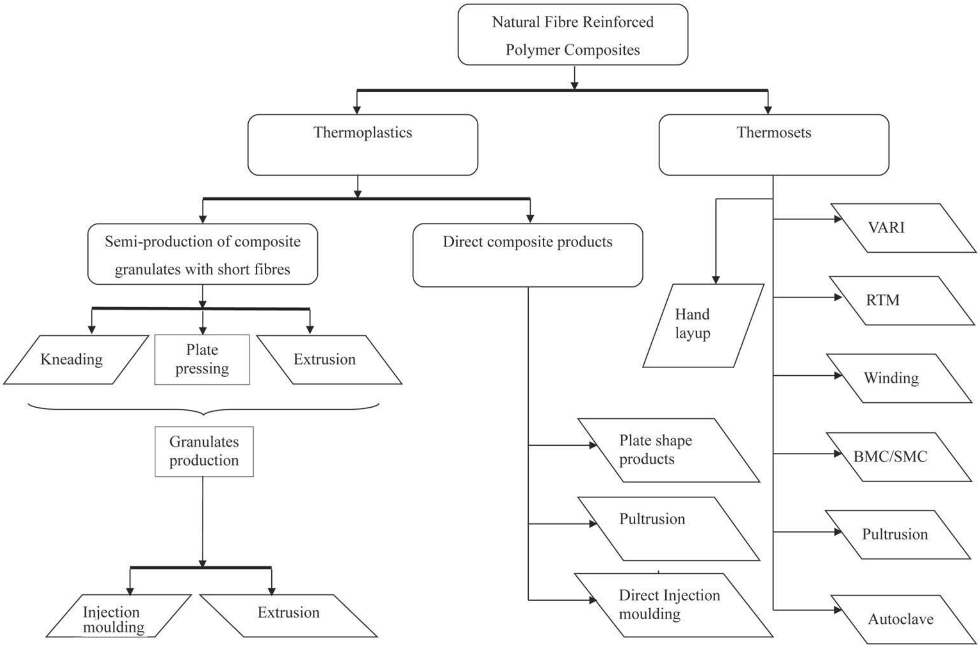


Figure 1: Classification of the processing techniques for natural fibre polymer composites.

Selection of the production technique depends on the required properties as well as the desired production rate. However, attention should be paid to the choice of processing parameters; these should be carefully selected due to the limited processing window for composites, as shown in Figure 2 (Ziegmann, 2005). Natural fibres degrade quickly at excessive processing temperature.

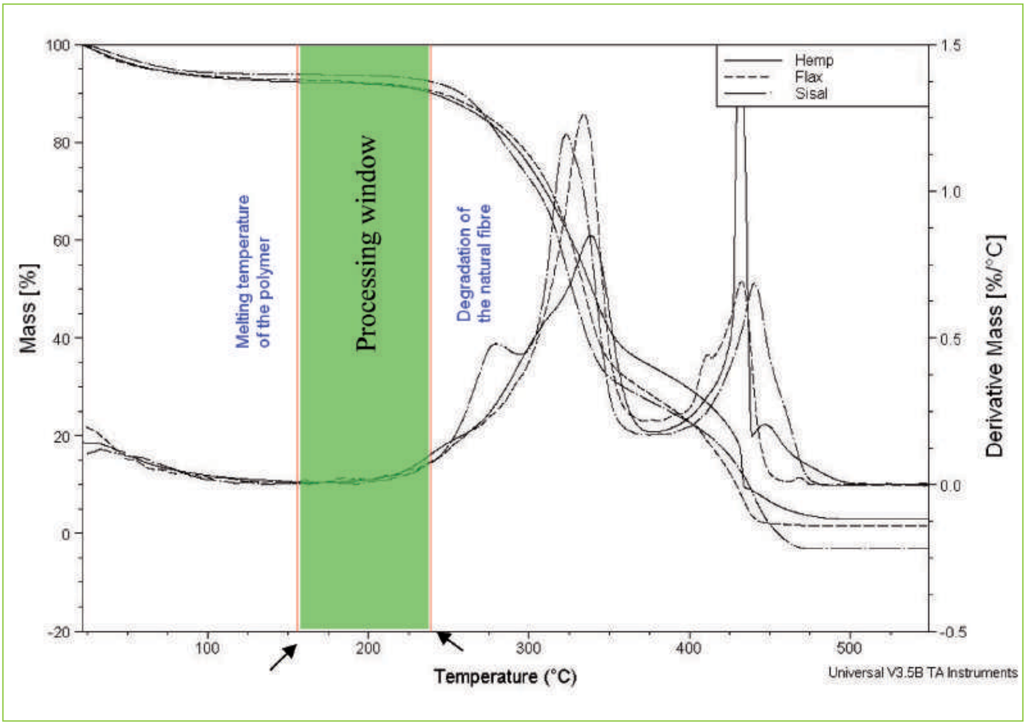


Figure 2: Processing window of natural fibre thermoplastic composite defined by TGA (Thermal Gravimetric Analysis). At the higher temperatures the natural fibres lose weight, which indicates thermal degradation.

1. Thermoplastic composites

The advantages of thermoplastic composites compared to thermosetting composites are:

- lower specific weight;
- recycling is possible;
- cleaner processing;
- unlimited storage time (cooling is not mandatory);
- formability without the need to manufacture a preform;
- application of welding techniques;
- reduced preparation for the mixture without need for chemical reaction.

Up to 60% volume fraction of fibres can be attained in thermoplastic composites. Selection of the production technique depends on the production rate and the product status (semi or finished). Injection moulding requires prepared composite granulates, whereas the pultrusion, filament winding and extrusion processes can deal directly with fibres (natural or synthetic) to have a profile product.
Also, the production technique affects the fibre aspect ratio and fibre orientation and hence the mechanical properties are defined. For instance, in pultrusion long and unidirectional fibres are attained within the produced profile. On the other hand, more randomness in the fibre directions is attained in extrusion and injection moulding. Figure 3 shows the different fibre product forms (raw, sliver, yarn, fleece or felts) and the different suitable manufacturing techniques as well as the effect of fibre technique on the production rate, fibre length and mechanical properties.

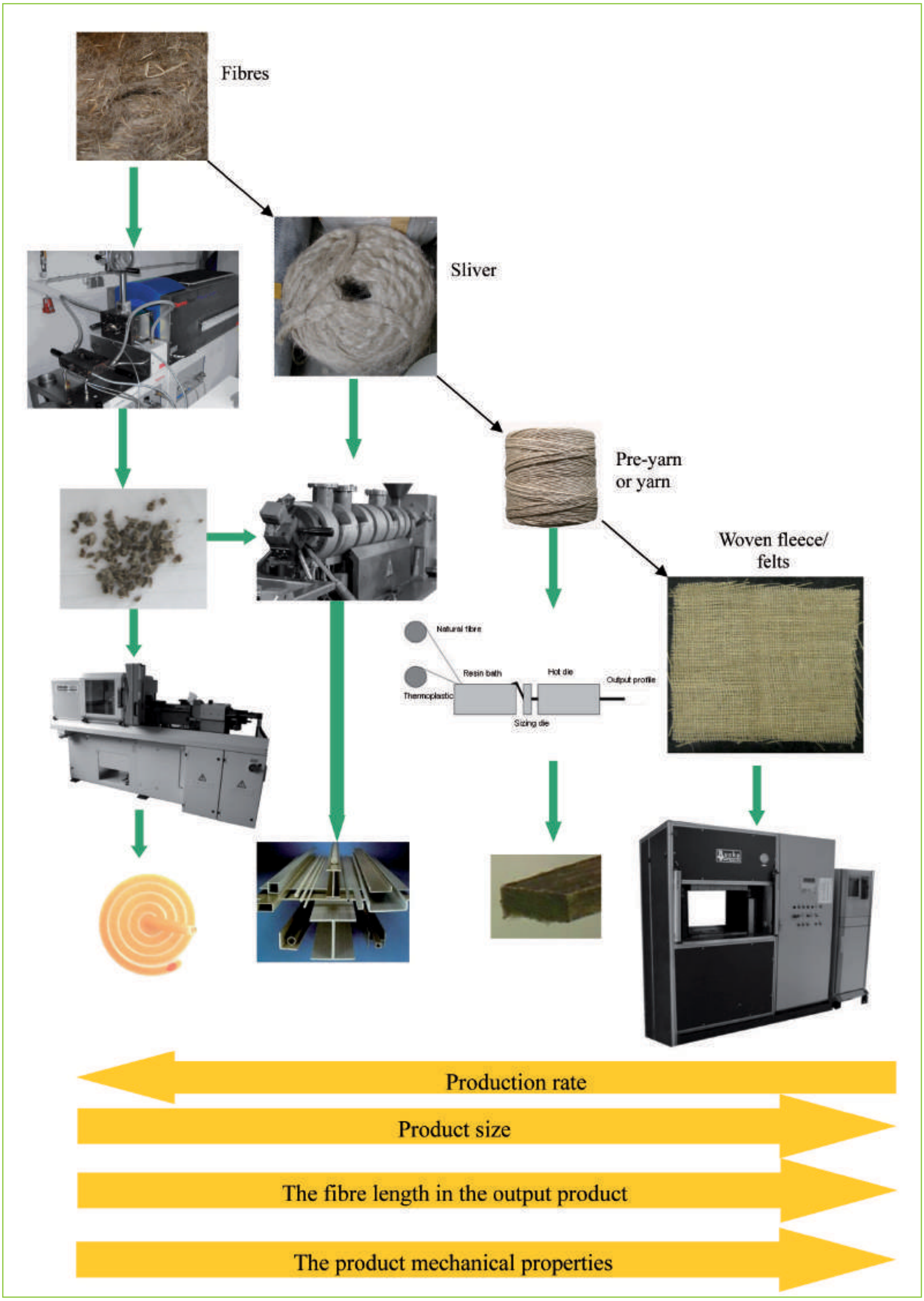


Figure 3: How product properties depend on the form of fibre product and the manufacturing technique used.

The influence of fibre length and orientation on the composite mechanical properties is illustrated in Equation 1, which gives a modified rule of mixture for the composite tensile strength. Similar equations can be given also to describe the composite overall stiffness (or E-modulus). The strength component related to the fibres increases with the increase of the fibre aspect ratio. A high aspect ratio guarantees more load transfer by the fibre. On the other hand, as the fibre orientation relative to the loading direction increases), the fibre strength component decreases. The previously described behaviour is shown in Figure 4 as reported by Pan et al [2].

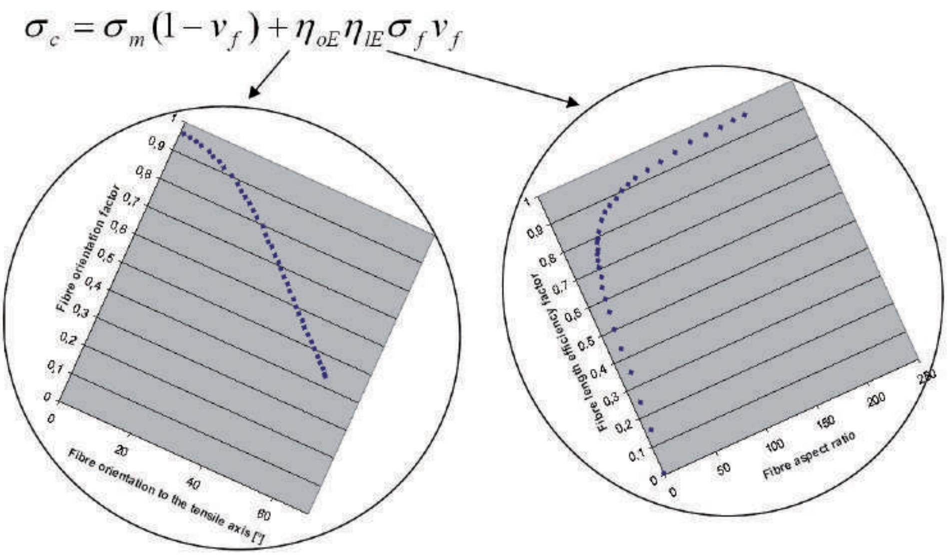


Figure 4: Composite mechanical properties as a function of fibre efficiency factors for fibre length and orientation.
(a) Effect of fibre orientation to the tensile axis; (b) Effect of fibre aspect ratio (length/diameter). For (a), as the fibre orientation becomes more coincident with the tensile axis (small angle approaches zero), the orientation factor increases, and hence the overall composite strength increases. For (b), as the aspect ratio increases, the fibre length efficiency factor increases, and hence the overall composite strength increases.

2. Semi-product composites (granulates)

a) Kneading

Kneading is a type of batch production (non-continuous) as shown in Figure 5. Shear force and temperature are applied to the fibres and the molten thermoplastic matrix to ensure a homogeneous distribution, Figure 6. The bulky composite compound out of kneading is granulated mechanically by a shredder. This process introduces fibre damage either by fibre kinking during kneading or by fibre cutting in the shredder, and hence the efficiency of fibrous reinforcement is decreased.

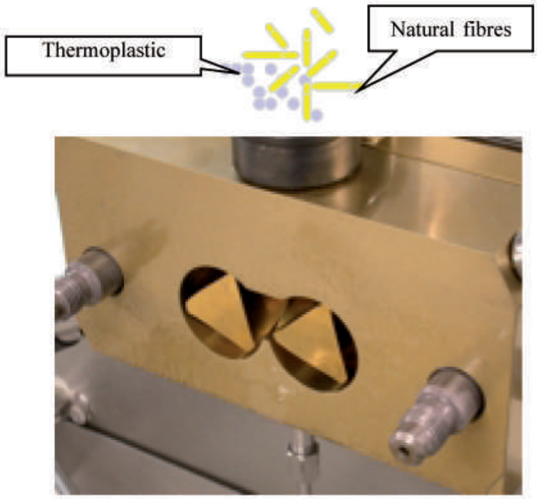


Figure 5: Mixing chamber of a roller-type kneader where natural-fibre thermoplastic composites are mixed.

Advantages:

- Accurate contents of fibre, matrix and other additives can be attained
- Suitable for low quantities, as it is job production tool
- Good distribution of fibres within the matrix

Disadvantages:

- Time consuming due to the low-volume mixing chambers
- Long-fibre composites cannot be produced by this method
- Damage of fibre due to excessive shearing and temperature
- Low production rates

b) Extrusion

The feeding of fibres into an extruder is still an unsolved problem. The available approaches depend on the fibre status. Extremely short fibres and wood flour are freely fed into the extruder. Slivers and yarns can be fed as illustrated in Figure 6. A where the sliver is fed to the thermoplastic stream through an input to the extruder or by the help of a side feeder which increases the input area. The side feeder guarantees better defibrillation of the fibres as well as gradual loading on the extruder. The homogeneity of the fibre distribution within the matrix is defined by the fibre loading, the applied temperature and the right selection of the extruder elements.

Advantages:

- High production rates
- Finished profile products or granulates can be attained

Disadvantages:

- Inaccurate fibre content due to the inconsistent linear density of the natural fibre roving
- Start-up phase takes time to reach stable production conditions
- Excessive shearing and temperature can damage fibres

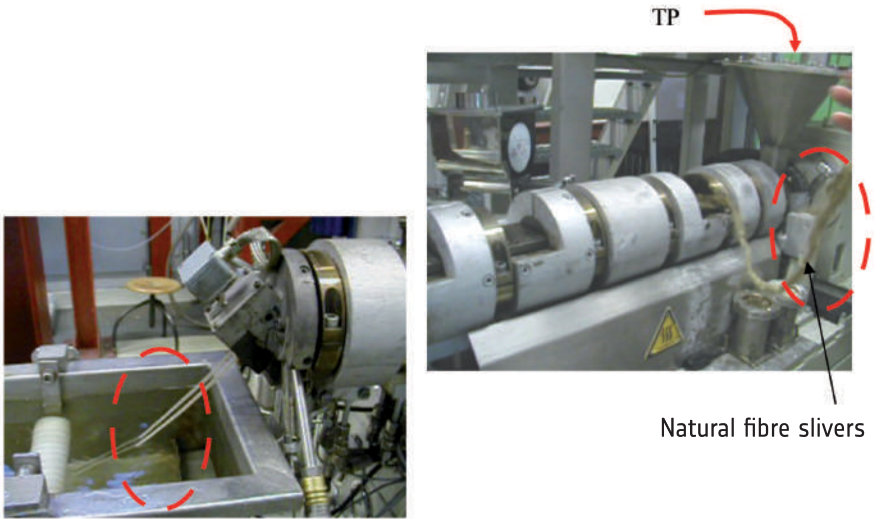


Figure 6: Extrusion of natural fibre sliver into the thermoplastic flow.

Figure 7 shows another way of continuously reinforcing thermoplastic polymers with natural fibres. Natural fibres can be inserted as fibre mat or even as chopped fibres, which are distributed evenly between the simultaneously extruded formable thermoplastic plates. A calendering process is then used to size and bond the sandwich structure. Finally, a cooling process is applied before cutting to standard-sized plates or pelletizing to granulates for further injection moulding.

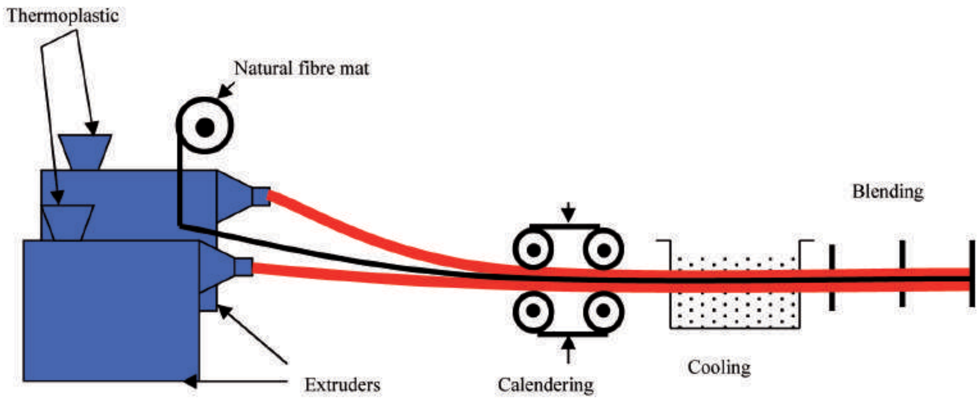


Figure 7: Continuous manufacturing of natural fibre reinforced thermoplastics as formable plates.

Advantages:

- High production rates for the continuous process
- Finished plates can be directly produced
- Woven and non-woven fabrics can be used as reinforcement

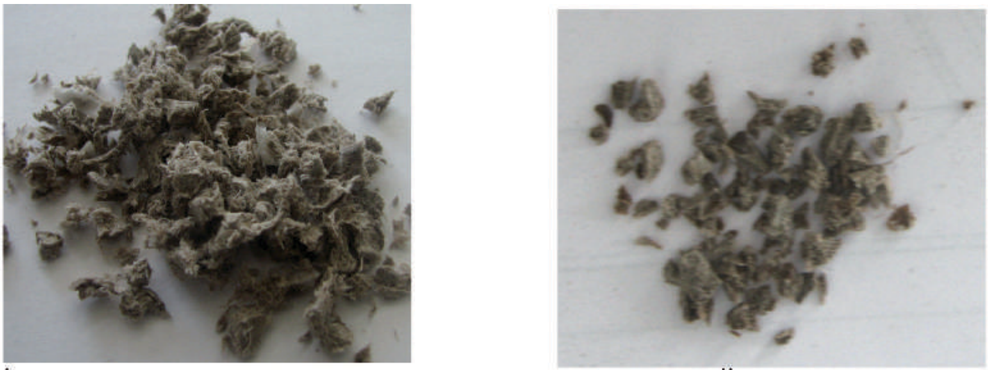
Disadvantages:

- Poor impregnation with thick fabrics, indicating that only low-volume-fraction composites are attainable
- High investment

3. Effect of the production technique on the granulate

a) Quality of the granulates

Inefficient binding between fibre and polymer results in a fluffy composite after pelletising. These granulates are not pourable or suitable for further injection moulding. This fault is due to the incorrect choice of extruder element (no kneading block), polymer deficiency, or insufficient coupling agent. Figure 8 shows the poor granulate quality resulting from insufficient bonding between fibre and matrix (right) and the good pourable granulates resulting from correct selection of the extruder elements, sufficient temperature, time and copolymer content (left).



i- ii-

Figure 8: Effect of the processing parameters on the quality of granulates after mechanical cutting:
i- fluffy, unsuitable for injection moulding process;
ii- properly cohesive granulates with pourable properties for injection moulding.

b) Fibre geometry

The composite mechanical properties are defined according to the final fibre geometry. For instance, in the press forming process, the fibres normally keep their technical size (about 70 μm diameter), whereas in the above-mentioned processes like kneading and extrusion, the fibres are reduced to more elementary sizes (about 15 μm) as shown in Figure 9.

4. Direct product thermoplastic composites

a) Compression moulding

Press forming of natural fibre thermoplastic composites is normally used in the automobile industry, especially in the inner cabin parts. The natural fibres are dissociated and blended with thermoplastic fibres. Then the blend is carded or air laid to get a fibrous web. Another way to have a hybrid fleece is the mechanical needling process, where natural fibres are introduced into the the thermoplastic fleece.
The fleece produced is preheated to a temperature ensuring low viscous flow of the polymer inside the natural fibre bundles. The fleece is then pressed to the required shape. The press is equipped with either a built-in hot plate or an external furnace to guarantee thermoplastic impregnation into the natural fibres. Figure 9 illustrates the process steps.

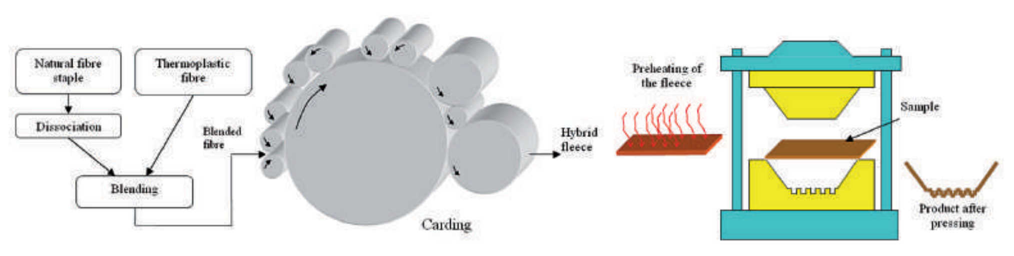


Figure 9: Schematic of the press forming technique for natural fibre reinforced thermoplastics.

Advantages:
- Fast process
- Complex structures can be produced

Disadvantages:
- Control of impregnation quality depends on the textile structure and thickness
- High investment

b) Pultrusion

Pultrusion is normally carried out either on separate rovings of natural fibres and thermoplastics or on fibre rovings from an intermingling process like Twintex®. The intermingled roving produced by a simultaneous roving process on natural and thermoplastic fibres (either by extruder or from another roving) is shown in Figure 10.

Pultrusion is carried out as shown in Figure 11. The natural-fibre volume is defined by the number of thermoplastic rovings compared to the number of natural-fibre rovings. The fibres are pretensioned, preheated and then introduced into the hot mould. Finally, a cooling procedure is applied to achieve the final size profile of the pultruded yarn composite.

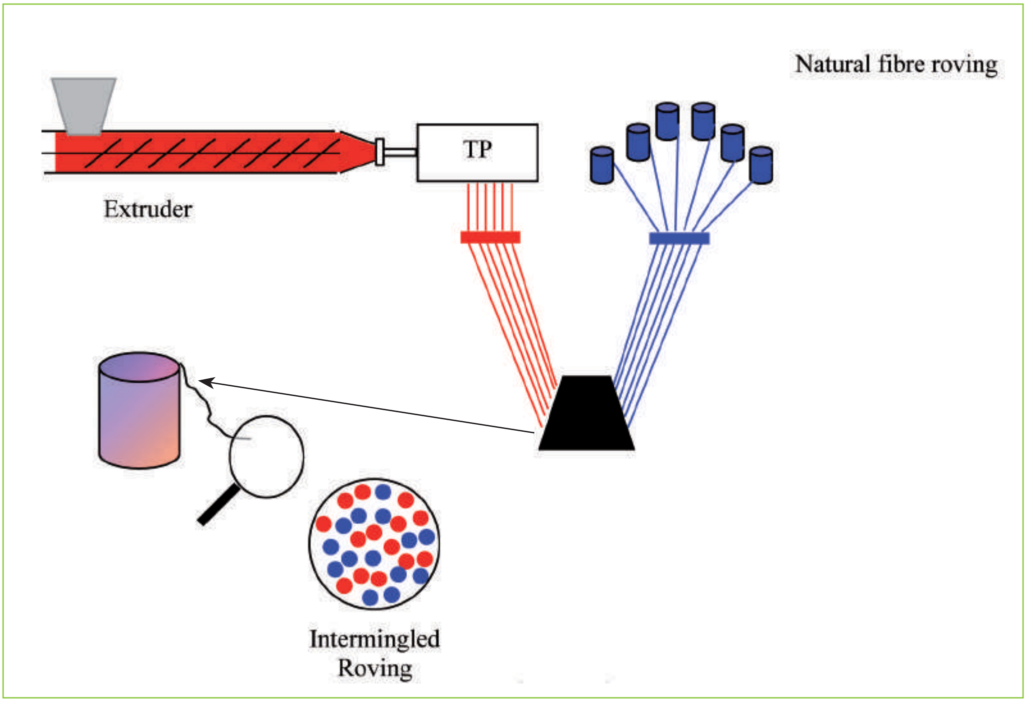


Figure 10: Manufacturing of Twintex-type roving.

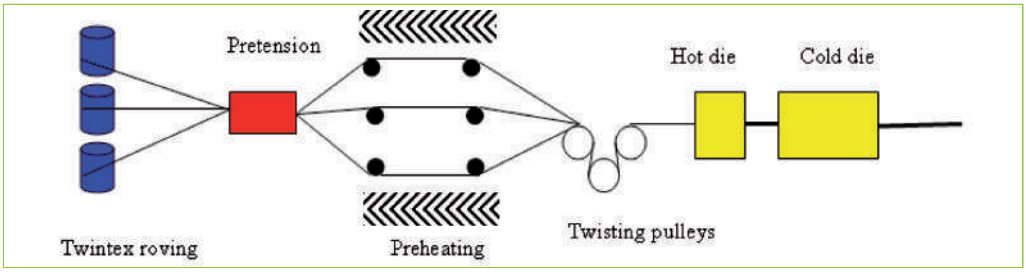


Figure 11: Pultrusion of natural fibre and thermoplastic fibres.

c) Direct injection moulding

A novel technique has been developed for direct injection moulding with natural-fibre sliver and TP granulates. This method is also widely named as direct long fibre reinforced thermoplastics (D-LFT). The process involves blending the fibres, thermoplastic and additives in a single stage, thus reducing cost. The process also improves product performance. A schematic for the direct injection technique is presented in Figure 12. KraussMaffei Company has developed another method for direct injection moulding, in which an extruder mixes natural-fibre bundles and the thermoplastic polymer together, close to what is illustrated in Figure 7. Then the extruded material is introduced directly into the injection mould.

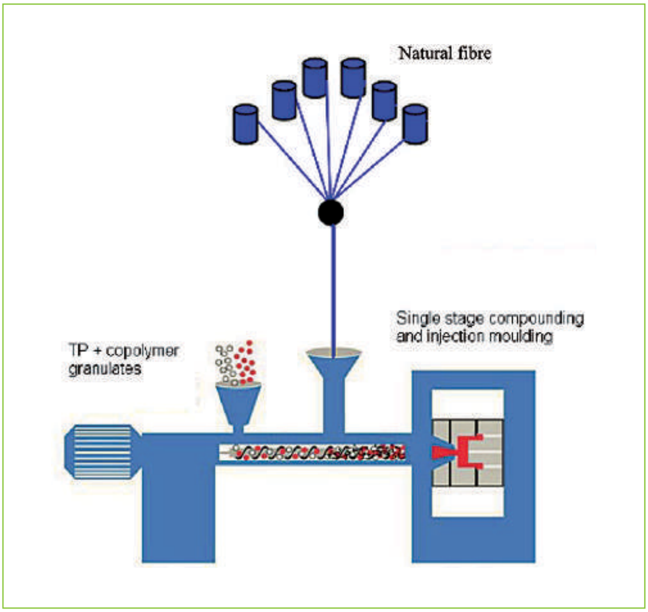


Figure 12: Direct injection moulding of natural fibre and thermoplastic granulates.

5. Thermosetting composites

Thermosetting natural fibre composites represent almost one third of the natural fibre composite applications (Nova Institute, 2007).

a) Hand lay-up

The hand lay-up method was developed in the USA 70 years ago. It is normally used on glass fibre fabrics with a final volume fraction of 30-50%. The usual thermosetting matrix is a catalysed accelerated polyester, although the use of vinylester and phenolics is also possible. The use of hand lay-up can also be extended to natural fibres (woven and non-woven fabrics). The principle of the hand lay-up method is shown in Figure 13 and carried out as follows: first, the mould surface should be cleaned, waxed and gel-coated, then the fabric is laid on the mould. Resin impregnation is done manually. Depending on the type of resin, resin curing can be heat-accelerated. Mould forming details are found in many references elsewhere (Reyne, 2009).

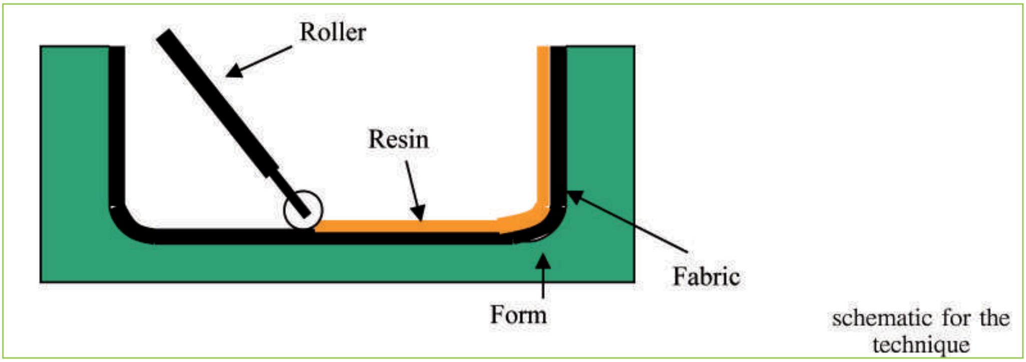


Figure 13: A schematic for the hand lay-up process.

Advantages:
- Simple practice procedures
- Relatively good surface
- Easy insertion of accessories
- Low investment

Disadvantages:
- Labour costs are higher, especially with the severe work conditions (resin fumes and cost of achieving healthy ventilation conditions)
- Product quality (dimensions, wrinkling, accurate fibre volume fraction) is dependent on human factors

b) Vacuum assisted resin infusion (VARI)

This process is normally applied with fabrics (woven or non woven). The multiple layers required for the natural fibre fabrics are first cut in the mould shape and then placed over the die. Fibres and mould are then vacuum-bagged. The resin is allowed to infuse into the fabric smoothly and slowly for wet out, assisted by the vacuum. After complete resin infusion, the natural fibre composites are left to cure under vacuum for 24 h at room temperature, after which they are unpacked and taken for inspection.

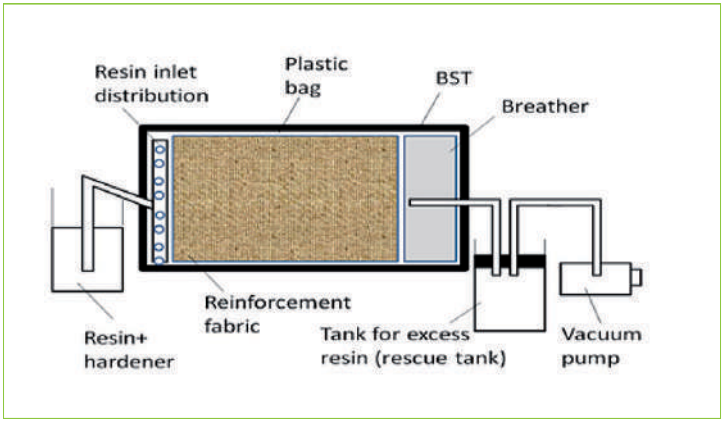


Figure 14: A schematic for a simplified VARI process.

Advantages:
- Higher degree of integration
- Possibility of producing large complex forms/structures

Disadvantages:
- Preparation is long due to absence of automation and also because the product must be demoulded after complete resin curing, removing all the accessories
- Higher costs because more accessories are required (vacuum pump, connections, resin distribution spirals, sealant material like tacky tapes, etc.)
- Probability of leakage leading to total loss of the product

Notes on the permeability of natural fibre fabrics

Infusion of natural fibre is problematic due to the nature of the natural fibre bundles, where both macro and micro infusion takes place around and inside the fibre respectively. The key factor in the success of the composite production is to have good impregnation of the resin into the matrix. This problem in fibre reinforced composites is called permeability.

Permeability represents resistance against fluid flow through porous media. Permeability can be described with Darcy's law as given in Equation 2:

$$V = -K \frac{\nabla P}{\eta} \qquad \text{Equation 2}$$

Where

V : Darcy's velocity vector

η : Newtonian viscosity of the fluid

∇P : Pressure gradient vector

K : Permeability tensor of the porous medium

From Equation 2; it is obvious that the permeability 'K' can be easily calculated from the steady state condition. This is done by measuring the volume flow rate and the pressure drop after complete filling.

The permeability of resin flow velocity through a textile is investigated before running experiments in order to define the permeability coefficients, model the resin flow, and ensure complete infusion before curing starts. Permeability testing is also helpful in defining the vacuum pressure required for resin infusion. Darcy-equation-based permeability experiments show that the permeability coefficients for woven jute fabrics of 205 and 385 g/m² are higher, but still comparable with the synthetic glass or carbon fibre fabrics at the same volume fraction.

This observation has been reported previously [Fakhirov, 2007] where a 30% volume fraction of untreated woven sisal has a permeability value of 6.38E-10, exceeding by 10-20% those of woven carbon and glass (5.66E-10 and 5.12E-10 respectively). Permeability results for wovens (205 and 385 g/m²) and mat are presented in Figure 15. Open-meshed woven fabric contributes to higher permeability, compared to the closed randomly chopped fibre mats.

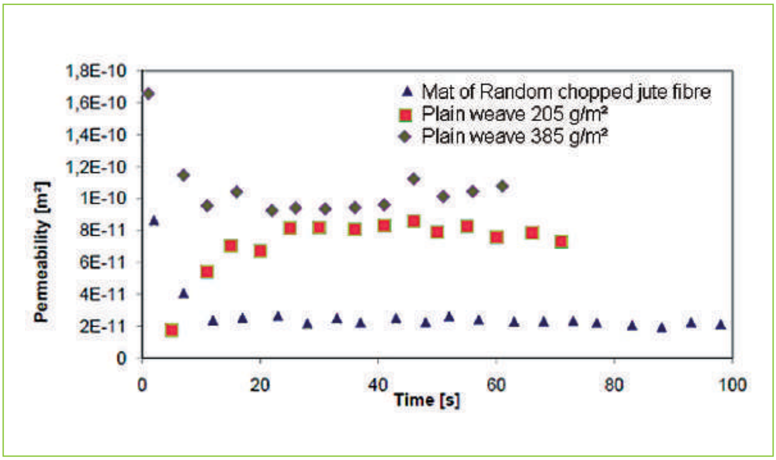


Figure 15: Summary of the global permeability test results using plant oil (sunflower) as a liquid to substitute epoxy resin with woven jute fabrics 205 and 385 g/m² and jute felt.

Notes on the drapability of natural fibre fabrics

Besides the infusion problem, the draping efficiency of natural fibre fabrics (the textile conformance to the underlying mould surface) represents a challenge, as the textile structure adds a constraint on the geometry replication accuracy.

Regarding the formability/drapability of the natural fibre fabrics, the usual problems posed by synthetic fibres are also present with the natural fibres. Factors like fabric weight, thickness and stiffness play an important role. The stiffness of the fabric depends in turn on other factors like weave construction and needle density. A soft fabric takes the form of the mould but makes ripples whereas the stiff one drapes away from the mould body, producing fewer ripples, but less accurate moulding.

On the level of the fibres, the following remarks are applicable to fibres:

- for fibre/yarn stiffness: high twisting increases stiffness of the textile and hence decreases drapability;
- for fibre size: increased thickness decreases drapability;
- for thread count (or linear density, tex): higher density decreases drapability.

To understand the influence of the overall textile design, the following chart can be helpful, as shown in Figure 16, which shows the effect of textile structure on both shear stiffness and draping behaviour. As expected, for most textiles, low shear stiffness imparts better drapability. The exceptions are uni-directional UD inlays/ tapes, which have low shear stiffness and low drapability. On the other hand, in nonwoven mat fabrics, the interlocking fibres impart high shear stiffness while the absence of textile structure results in high drapability. Two-dimensional knitted fabrics have high drapability due to the strain ability of the knitted filaments, while 3D wovens are subject to a lot of strain constraints, which impairs the draping quality.

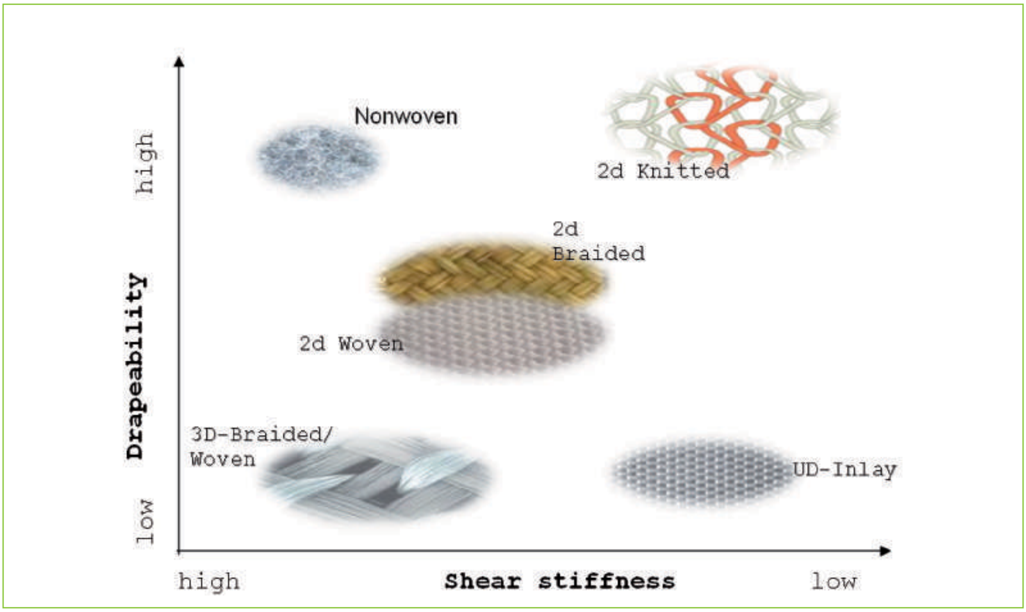


Figure 16: Effect of the fabric type on drapability.

c) Resin transfer moulding RTM

RTM was been developed as a production technique back in the 1970s. It resembles the VARI method, except for the applied pressure, which is in the 1-5 bar range. In the RTM technique, resin and hardener are pumped separately to the mixing head before injection into the mould and curing, as shown in Figure 17. In VARI, air removal during the pre-vacuum treatment helps to eliminate air bubbles from the product, which affects the composite surface quality and strength properties.

Advantages compared to the hand lay-up technique:

- More accurate dimensions
- Less material waste
- Surface quality is good for both of the product surfaces rather than a single surface as with the hand layup or VARI techniques
- Higher production rate
- Reproducible production due to the use of a closed mould with the same input and output locations
- Fewer resin fumes

Disadvantages:

- The use of a pressure of 1-5 bar in the moulds rules out the production of large products
- Requires greater investment, i.e. high-precision male and female moulds, which are mandatory
- Early detection of fabric defects is difficult

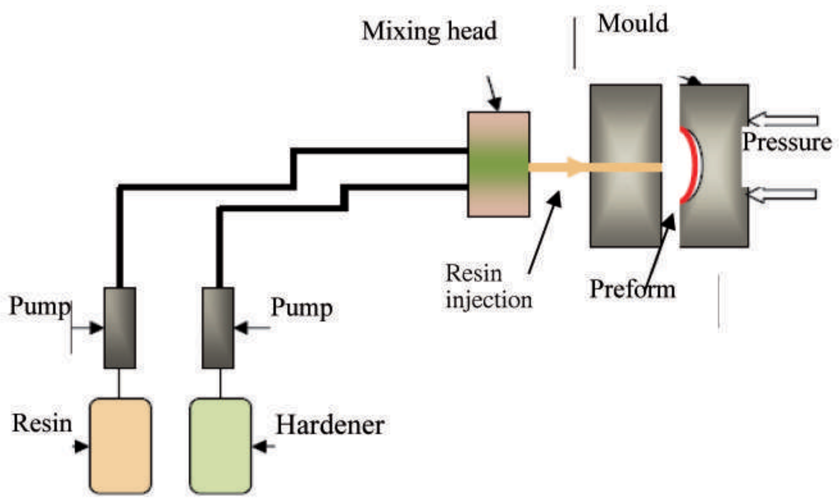


Figure 17: A schematic view of RTM technique.

d) Bulk moulding compound BMC

BMC is simply a hot, closed flow forming technique. The BMC-material consists of 15-25% chopped fibres impregnated with resin (normally polyester) by stirring and/or kneading before the production. This compound can also be stored for up to 2 months. This represents a positive point for industry needs. The material is put between the two heated parts of the moulds and then the heated mould is closed and pressure, and pressure is applied. The bulk moulding compound then flows to fill the mould cavity and the temperature assists the curing process. Figure 18 shows a schematic of the process.

Advantages:

- Use of semi-finished products
- Less time consuming
- Less need for qualified labour
- Both surfaces of the product have good smooth quality

Disadvantages:

- Low storage time
- Presence of micro bubbles
- High investment because the press used should withstand 50-120 bar for areas up to 2m².

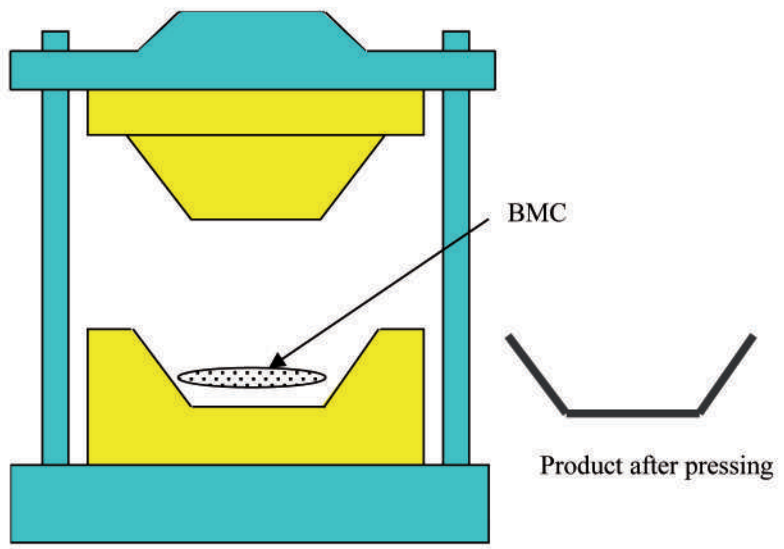


Figure 18: BMC schematic.

e) Sheet moulding compound SMC

SMC is also a hot press flow forming technique like BMC, with the exception that the pre-impregnated material takes the shape of foil or sheet. The sheet is manufactured as shown in Figure 19. In this process, longer fibre length can be used, which imparts higher mechanical properties. Figure 20 shows a schematic of the SMC hot press technique.

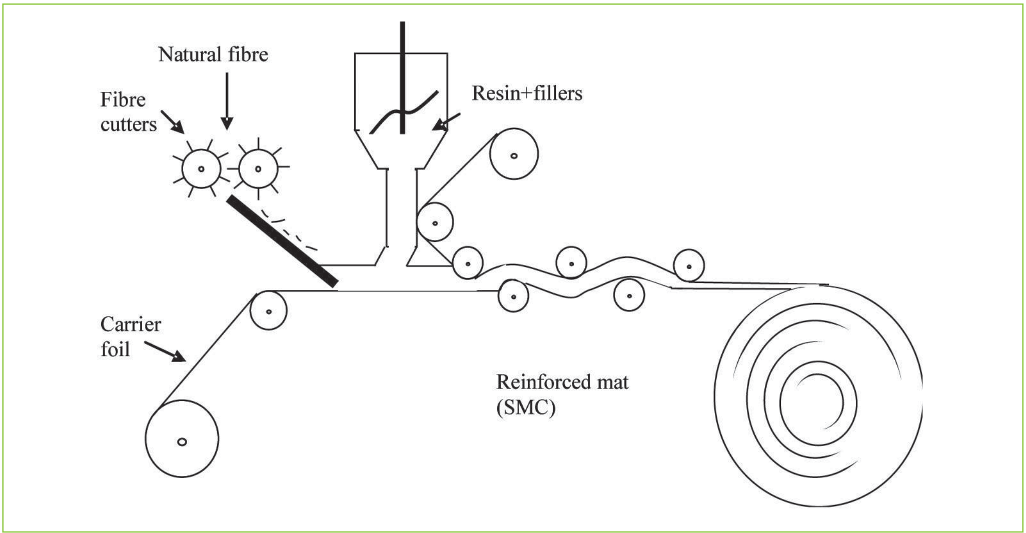


Figure 19: SMC manufacturing.

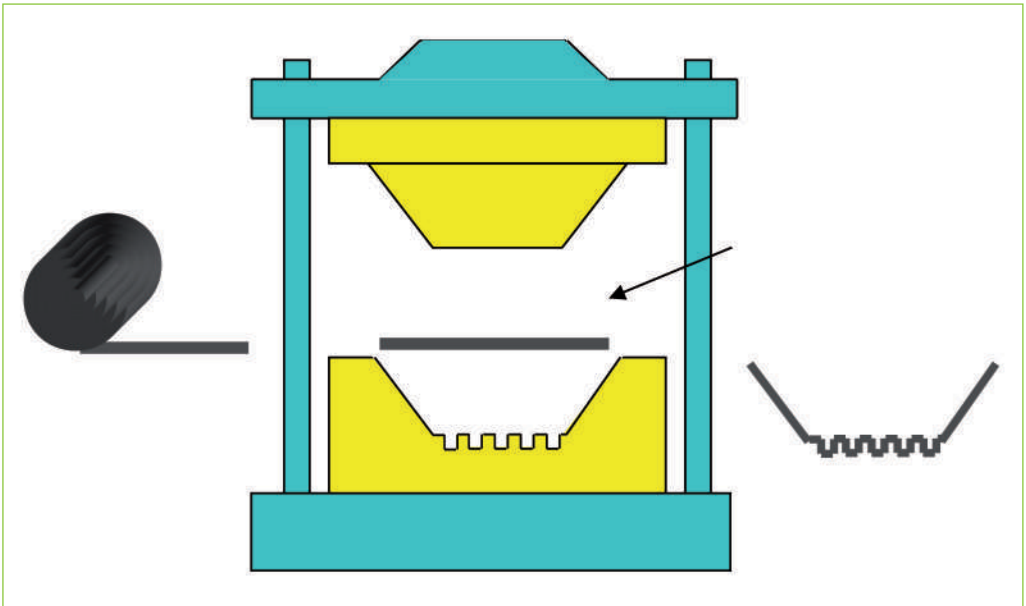


Figure 20: SMC schematic.

Advantages:
- The same advantages of BMC
- Higher mechanical properties in comparison to BMC, and a higher reinforcement volume fraction (up to 30%) can be used
- More complex surfaces can be manufactured

Disadvantages:
- Low storage time

- Presence of micro bubbles
- High investment

f) Pultrusion

The pultrusion process can be used with natural fibre and thermosetting resin, as shown in Figure 21. Natural fibre rovings are placed on a creel (Akil, 2009) (Reyne, 2008) and equipped with a roving guide to lead the fibre strands into the resin bath (unsaturated polyester or epoxy). The fibres are impregnated with the thermosetting resin before they are cured in a heated steel die (120-160°C for polyester and 200-220°C for epoxy). The strands are pulled through the die with the required profile and cut into the desired profile length.

Advantages:
- High volume fraction of spun yarn fibres up to 70%
- The almost continuous fibres ensure higher mechanical properties and efficient load carriage
- Very good surface quality

Disadvantages:
- Low production rates because the speed of pultruded profiles is correlated with the curing rate
- Production launch phase is long
- High investment for the machine installation

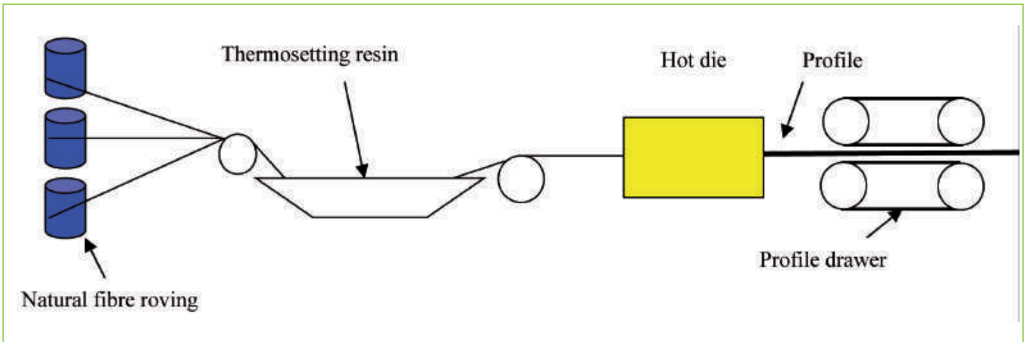


Figure 21: Pultrusion schematic of natural fibre thermosetting composites.

g) Winding

Winding of natural fibres over a rotating mandrel is called “filament winding”. A schematic is shown in Figure 22 to illustrate the process concept. Fibres are in the form of roving. The fibres are pulled into a resin bath for impregnation. The impregnated fibres are wound afterwards around the mandrel with the desired shape.

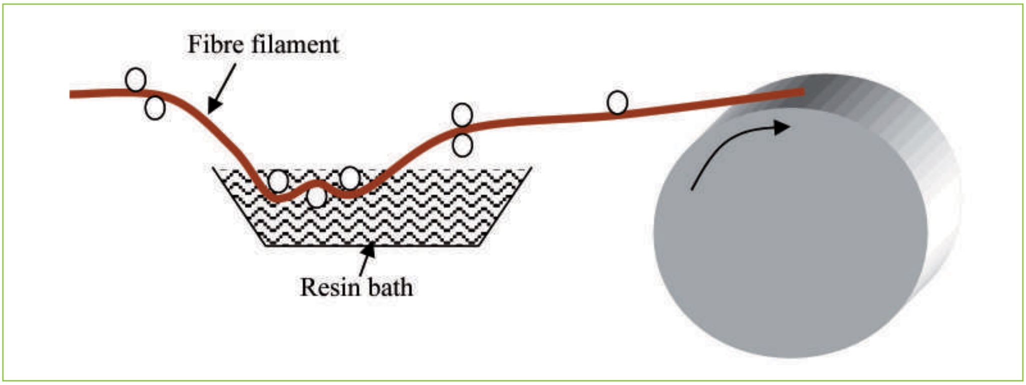


Figure 22: Filament winding schematic of natural fibre thermosetting composites.

Advantages:
- The reproducibility of the fibre position accuracy
- Use of continuous fibres results in high strength
- Large workpieces may be used

Disadvantages:
- The mandrel must be removed after the winding process

h) Autoclave

The autoclave process implies the use of temperature, vacuum and positive pressure on laminated resin-impregnated fabric layers. The laminates are cut into the required size. Then the laminates are placed in the autoclave and the chamber is closed. Vacuum pressure is applied to get rid of the resin fumes. Positive pressure and temperature are applied on the laminate to start the curing process. A schematic of this process is given in Figure 23.

Advantages:
- Consistent reproducible fibre content, with the possibility to reach a reinforcing fibre volume fraction up to 60%
- Highly stiff composite structure
- High specific strength to weight ratio

Disadvantages:
- The need to cut the laminate fabric layers into the required shape before autoclaving
- Long preparation time in addition to the autoclaving time, resulting in a long production cycle
- Requires high investment

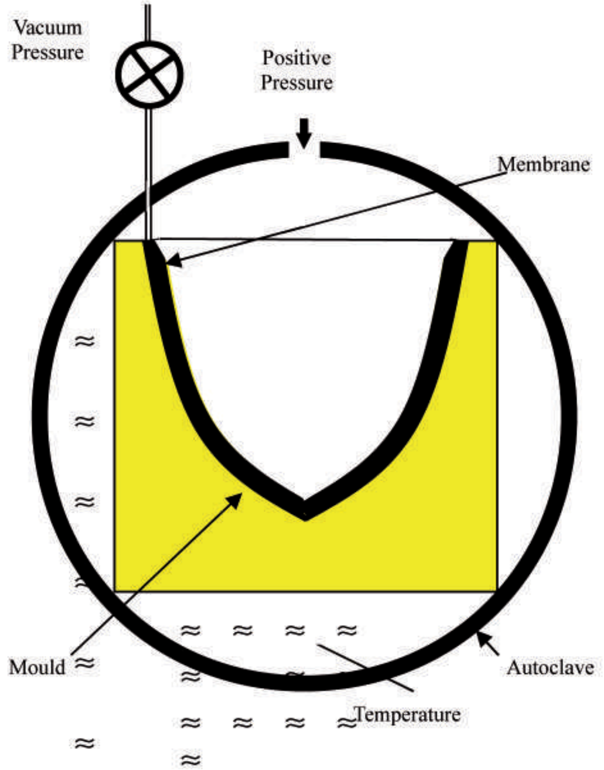


Figure 23: A schematic of the autoclave process.

6. Acknowledgement

Thanks are due to Dr Eng Ahmed El-Sabbagh for his help in editing this text. Also thanks to the natural fibres group headed by Dr Leif Steuernagel for their results presented in this work.

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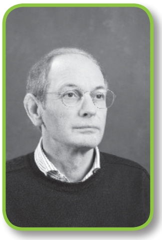
- VII - Properties of flax and hemp composites



Hans Lilholt,
Chief Scientist,
Materials Research Division, Risø DTU, Denmark

Bo Madsen,
Senior Scientist,
Materials Research Division, Risø DTU, Denmark

1. Cellulose fibres

The fibres that can be extracted from flax and hemp plants are strong, stiff fibres, and therefore they offer the opportunity to be used as reinforcing fibres for composites. The fibres are "mixed" with a polymer matrix to form a combined material, which is called a composite.

The basis for the strength and stiffness of the flax and hemp fibres is their composition of cellulose, hemicelluloses and lignin. Of these, the cellulose is the important part, because it has the high strength and stiffness, while the hemicelluloses and lignin form a sort of "glue", holding the cellulose units (microfibrils) together and allowing them to work in combination.

Typical compositions of cellulose fibres are listed in Table 1. It is noted that the flax and hemp fibres have high cellulose content (70–80%), and thus they have the best potential to form strong, stiff fibres for composites.

- Table 1 -
Composition of cellulose fibres

Fibre	Major chemical components in mass %		
	Cellulose	Hemicellulose	Lignin
Hemp	75	20	5
Flax	80	15	5
Wheat straw	40	30	20
Soft wood	40-50	20-30	25-35
Hard wood	40-50	25-40	20-25

The hierarchical relationship between the stem of the plant and the cellulose microfibrils is described in Chapter 2. The molecular structure of cellulose microfibrils is shown in Figure 1.

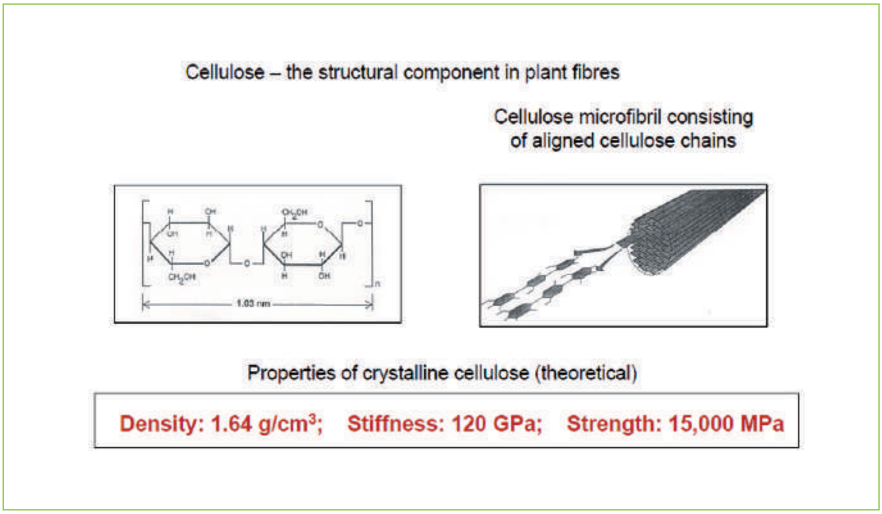
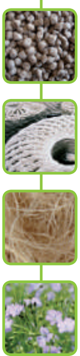


Figure 1: The molecular structure of cellulose microfibrils is based on the unit of two glucose molecules, and it has total dimensions of about 1 nm. The theoretical maximum properties of crystalline cellulose are given.

The cellulose microfibrils form crystalline structures with an orderly arrangement of the individual glucose molecules. The theoretical maximum properties of this perfect crystalline cellulose are listed in Fig. 1; it is noted that the density is at a maximum of 1.64 g/cm^3, and that the stiffness and strength are extremely high with values of 120 GPa and 15,000 MPa, respectively. The practical properties for some cellulose-based fibres, including flax and hemp, are listed in Table 2.

- Table 2 -
Properties of cellulose fibres

Fibre type	Density g/cm^3	Stiffness GPa	Strength MPa
Hemp	1.5 – 1.6	30 – 60	300 – 800
Flax	1.5 – 1.6	50 – 70	500 – 900
Jute	1.3 – 1.5	20 – 55	200 – 500
Sisal	1.2 – 1.4	9 – 22	100 – 800
Cotton	1.5 – 1.6	6 – 10	300 – 600
Softwood	1.2 – 1.4	10 – 50	100 – 170
Cellulose fibres	1.5	50	800
Cellulose microfibrils	1.64	120	15,000
Glass fibres	2.6	70	3,500
Carbon fibres	1.8	800	2,500



The range of properties shown for the different types of plant-based cellulose fibres is due to the different origins and handling procedures for different batches of fibres; for a given batch quality, the properties are more well defined. The term "cellulose fibres" in Table 2 indicates the average values for the properties.

It is noted that the practical stiffness for cellulose fibres, in particular flax and hemp, is about one half of the theoretical value, while the practical strength values are much lower that the theoretical strength. The cellulose fibres can "compete" with traditional fibres like glass fibres and carbon fibres, on the basis of their very low density.

2. Cellulose fibre composites

In general, composite materials are formed from fibres and a matrix, which binds the fibres together and transfers the external load to the fibres. The properties of the composites are governed by both the properties of the individual parts (fibres and matrix) and by the ratio and configuration in which these parts enter the composite. The principle is illustrated in Fig. 2, where several of the important parameters for the mechanical properties are listed.

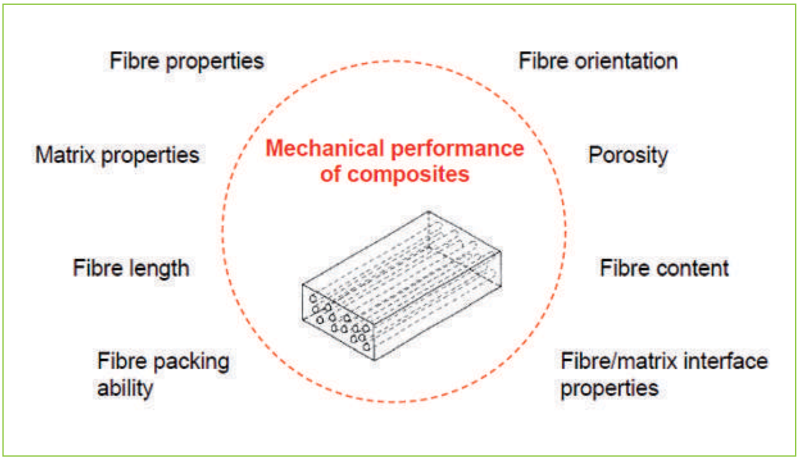


Figure 2: The performance of composites with cellulose fibres in a polymer matrix is governed by a range of parameters.

The properties of importance for composites in general will be addressed in the following section, with a special focus on flax and hemp composites.

3. Mechanical properties: stiffness and strength

A composite with all fibres parallel in one direction is called a uni-directional (UD) composite, and it is a basic and useful form to elucidate the mechanical properties of composites.

The stiffness can be calculated from the equation:

$$E_c = V_f \times E_f + V_m \times E_m \qquad (1)$$

The strength can be calculated from the equation:

$$\sigma_c = V_f \times \sigma_f + V_m \times \sigma^*_m \qquad (2)$$

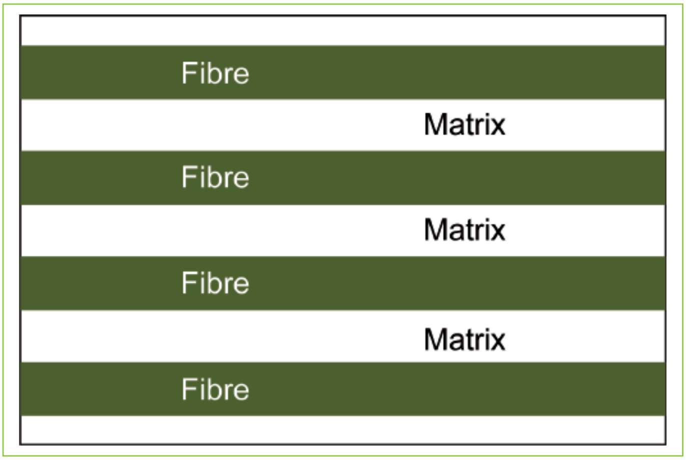


Figure 3: The basic composite unit consists of parallel fibres (green) in a matrix, and is used to evaluate the mechanical properties.

The composite values (E_c, σ_c) are governed by the volume fraction of fibres (V_f) and of matrix (V_m) as well as the properties of the individual parts, E_f and σ_f for fibres, and E_m and σ_m for matrix. In these equations the porosity is assumed to be zero, such that $V_m = 1 - V_f$. In equation (2), the matrix stress at failure of the composite σ^*_m is normally slightly smaller than the failure strength of the matrix itself, as shown in Fig. 4.

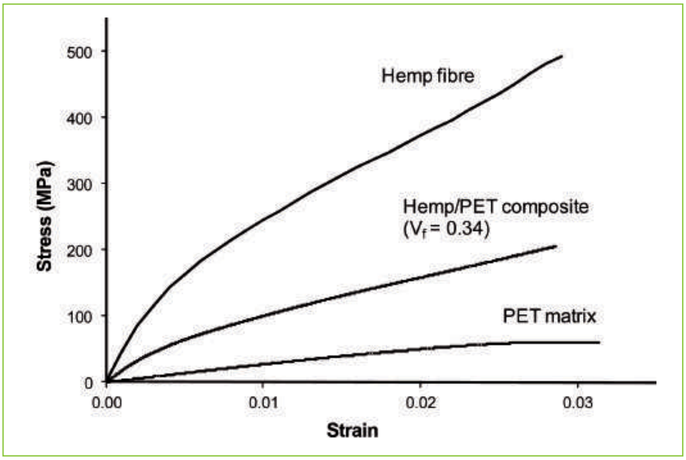


Figure 4: Loading curve for stress as a function of strain for hemp fibre, PET matrix and the hemp/PET composite. At each strain value, the composite stress is calculated from the fibre stress and the matrix stress, according to equation (2).

The importance of fibre volume fraction, as expressed in equations (1) and (2), is shown in Fig. 5 for cellulose fibre composites as compared to glass fibre composites. Fig. 5a shows stiffness values and Fig. 5b shows strength values.

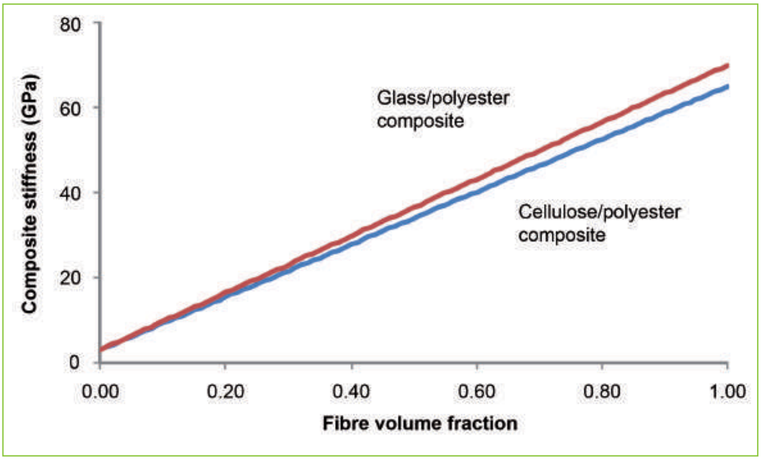


Figure 5a: The <u>composite stiffness</u>, as calculated from equation (1), is a linear function of fibre volume fraction for UD-composites. Cellulose fibre composites are compared to glass fibre composites. The material values are: cellulose fibre stiffness 65 GPa, glass fibre stiffness 70 GPa, polymer matrix stiffness 3 GPa.

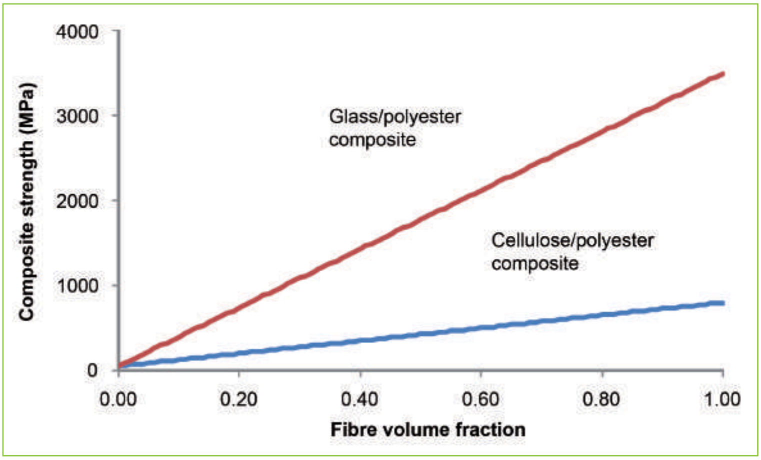


Figure 5b: The <u>composite strength</u>, as calculated from equation (2), is a linear function of fibre volume fraction for UD-composites. Cellulose fibre composites are compared to glass fibre composites. The materials values are: cellulose fibre strength 800 MPa, glass fibre strength 3500 MPa, polymer matrix strength 50 MPa.

4. Physical properties: density

The composite density is calculated from the equation:

$$\rho_c = V_f \times \rho_f + V_m \times \rho_m \qquad (3)$$

The composite value for density is governed by the volume fraction of the fibres V_f and of the matrix V_m, as well as the density of the individual parts, ρ_f for the fibres and ρ_m for the matrix. For composites with cellulose fibres from flax or hemp and a polyester matrix, the typical densities are in the range 1.3 g/cm^3 to 1.4 g/cm^3 for fibre volume fractions of 30 to 60%. The full range of densities, according to Equation (3), are shown in Fig. 6, and compared to glass fibre composites.

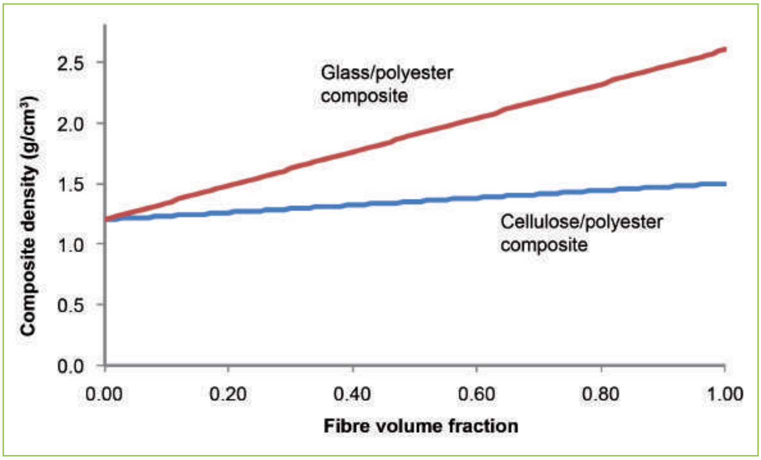


Figure 6: The composite density, as calculated from equation (3), is a linear function of fibre volume fraction, for cellulose fibre composites and for glass fibre composites. The material values are: cellulose fibre density 1.5 g/cm^3, glass fibre density 2.6 g/cm^3, polymer matrix density 1.2 g/cm^3.

5. Chemical properties: moisture absorption

The cellulose fibres will absorb a fairly large amount of moisture from the surrounding atmosphere (rather more than glass fibres, for example, which absorb nearly no moisture).

The polymer matrix will also absorb moisture, but normally less than cellulose fibres.

The moisture content M is measured as weight of absorbed moisture relative to the dry weight of material (cellulose, polymer), and given as a percent value. The moisture content is dependent on the relative humidity of the surroundings. The moisture content of materials is presented by curves in a diagram, where moisture content is a function of relative humidity, as shown in Fig. 7.

At any given relative humidity, the composite value for absorption (M_c) is governed by the values for fibres (M_f) and for matrix (M_m), and can normally be calculated according to the equation:

$$M_c = W_f \times M_f + W_m \times M_m \quad (4)$$

It is noted that this equation has the same form as the equations (1), (2) and (3), but that it is based on the *weight* fractions for fibres (W_f) and matrix (W_m). The composite curve in Fig. 7 is the calculated curve for 50 weight percent of fibres in the composite.

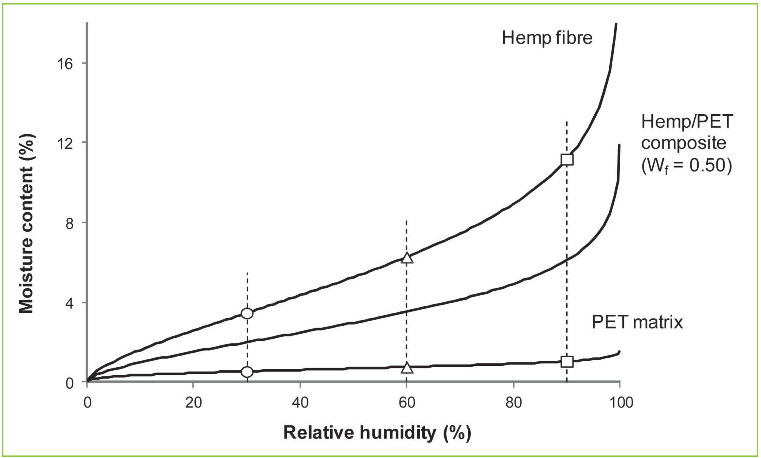


Figure 7: The moisture contents of hemp fibres, PET matrix and hemp/PET composite (at 50% weight fraction) are plotted as a function of relative humidity. The S-shaped curves are typical for moisture absorption in materials.

In Fig. 8 the relationship from equation (4) is plotted for three different relative humidities of 30%, 60% and 90%, as marked in Fig. 7. The values for the pure matrix and the pure fibres are marked with the same symbols in Fig. 7 and Fig. 8, and the straight lines connecting these points in Fig. 8 represent the composites at each relative humidity value.

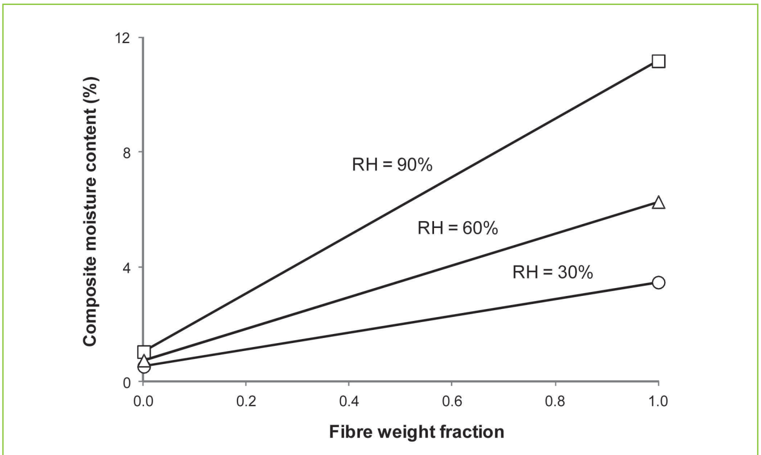


Figure 8: The linear relationship of equation (4) for cellulose fibre composites is shown for three different values of relative humidity, RH = 30%, RH = 60%, and RH = 90%. At weight fraction 0.0 the three markings indicate the corresponding data points of the matrix curve in Fig. 7. At weight fraction 1.0 the three markings indicate the corresponding data points of the fibre curve in Fig. 7.

6. Mechanical properties relative to density

From the expression for stiffness, equation (1), and for strength, equation (2), in combination with the composite density equation (3), it is possible to calculate the mechanical property value relative to the corresponding density for the composite; these ratios are often called specific stiffness and specific strength, respectively, and are presented in Figs. 9 and 10. It is noted that the specific stiffness and the specific strength are not linear functions of the fibre volume fraction. The shape of the curve depends on the ratio between the densities of fibres and matrix.

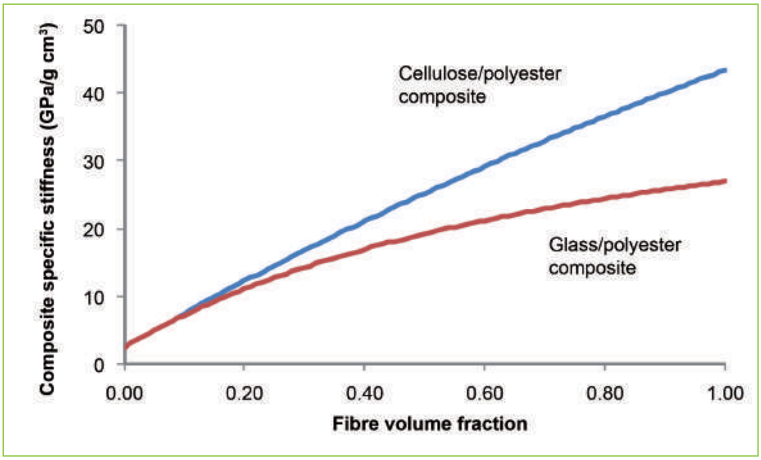


Figure 9: The specific composite stiffness as a function of fibre volume fraction for UD composites. Cellulose fibre composites are compared with glass fibre composites. The material values are: cellulose fibre stiffness 65 GPa, glass fibre stiffness 70 GPa, polymer matrix stiffness 3 GPa, cellulose fibre density 1.5 g/cm^3, glass fibre density 2.6 g/cm^3, polymer matrix density 1.2 g/cm^3.

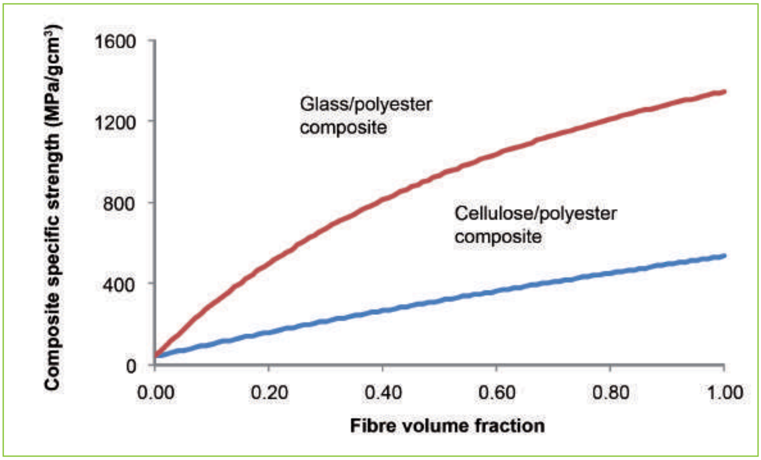


Figure 10: The specific composite strength as a function of fibre volume fraction for UD composites. Cellulose fibre composites are compared with glass fibre composites. The material values are: cellulose fibre strength 800 MPa, glass fibre strength 3500 MPa, polymer matrix strength 50 MPa, cellulose fibre density 1.5 g/cm^3, glass fibre density 2.6 g/cm^3, polymer matrix density 1.2 g/cm^3.

The specific stiffness is better for cellulose fibre composites than for glass fibre composites, while the specific strength is better for the glass fibre composites.

7. Composites with short fibres

For composites with short fibre, the effect of fibre ends becomes of increasing concern, and relations are established for this effect. The equation (1) for composite stiffness is modified by the use of a fibre length efficiency factor. The effect of fibre length (in mm length) on the composite stiffness is illustrated in Fig. 11. The curves show that the stiffness reduction is only significant at very short fibre lengths, below 1 mm. The lengths of flax and hemp fibres are normally in the range of 5–50 mm, and therefore the calculation of stiffness for flax- and hemp-fibre composites needs not be corrected for fibre length.

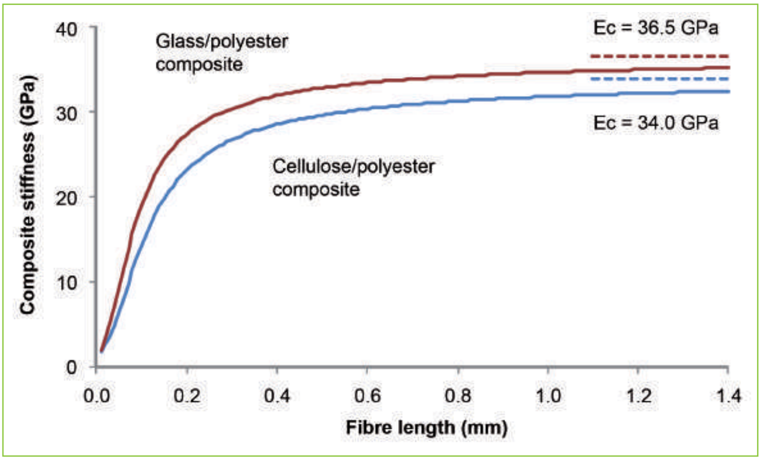


Figure 11: The calculated composite stiffness as a function of fibre length (in mm). Cellulose fibre composites are compared with glass fibre composites. The dotted horizontal lines indicate the stiffness value at infinite fibre length. The material values are: cellulose fibre stiffness 65 GPa, glass fibre stiffness 70 GPa, cellulose fibre diameter 20 µm, glass fibre diameter 15 µm, polymer matrix stiffness 3 GPa, polymer matrix shear stiffness 1 GPa, composite fibre volume fraction 50%.

In the same way as for stiffness, the effective strength of the fibres is reduced due to non-loading at the fibre ends. A certain critical fibre length l_c is defined such that a fibre with this length is loaded to its failure stress at its midpoint, and the expression is:

$$l_c / d = \sigma_{fu} / 2 \tau_i$$

where d is the fibre diameter, σ_{fu} is the fibre failure stress and τ_i is the interface shear stress between fibre and matrix. Fibres with lengths below the critical length can not be loaded to failure in a composite. At fibre lengths shorter than the critical length, the composite strength depends strongly and linearly on fibre length, while at longer fibre lengths the composite strength approaches the strength value for very long (infinite) fibre lengths. It is noted that the critical fibre length is very short (for cellulose fibres 0.4 mm, for glass fibres 0.7 mm), so that in practice most cellulose fibres can be considered to be long, and the simple equation (2) can be used as a very good approximation.

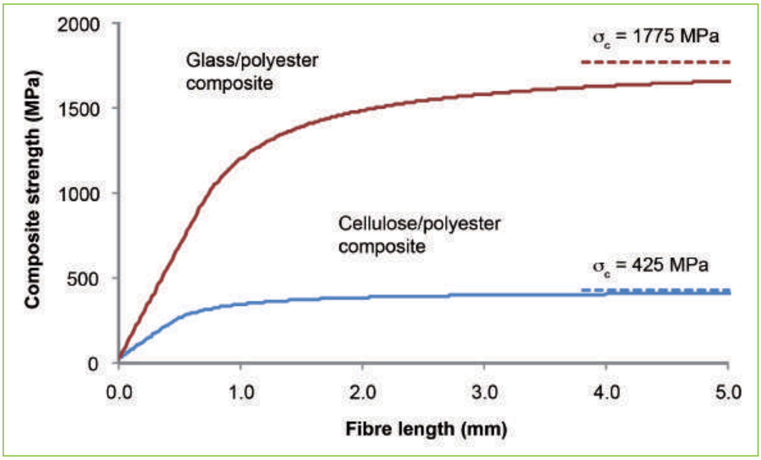


Figure 12: The calculated composite strength as a function of fibre length (in mm). Cellulose fibre composites are compared with glass fibre composites. The dotted horizontal lines indicate the strength value at infinite fibre length. The material values are: cellulose fibre strength 800 MPa, glass fibre strength 3500 MPa, cellulose/polymer interface strength 20 MPa, glass/polymer interface strength 40 MPa, cellulose fibre diameter 20 µm, glass fibre diameter 15 µm, polymer matrix strength 50 MPa, composite fibre volume fraction 50%.

8. Composites with non-aligned fibres

Fibres can be present in a composite in non-aligned fibre arrangements. If the fibres form a random two-dimensional planar arrangement (2-D), their effect in all directions of the plane is only 1/3 of the effect for fully aligned fibres, and therefore the corrected fibre stiffness 1/3 E_f is used. For a random three-dimensional spatial arrangement (3-D), the corresponding factor is 1/6. A calculation, based on a modified form of equation (1) including the fibre orientation efficiency factor, gives the following values in Table 3 for the UD-arrangement, the 2-D arrangement, and the 3-D arrangement for composites with fibre volume fraction 50%.

- Table 3 -
Stiffness of composites with non-aligned fibres

Composite stiffness	Cellulose fibre composites	Glass fibre composites
E_c (UD)	34 GPa	37 GPa
E_c (2-D)	12 GPa	13 GPa
E_c (3-D)	7 GPa	7 GPa

It is clear that a large reduction occurs for the non-aligned fibres, and that alignment of fibres is a very efficient way to obtain good mechanical properties, for a given amount of fibres. It is also noted that the difference between cellulose fibre composites and glass fibre composites is rather small for both 2-D and 3-D fibre arrangements.

9. Composites with off-axis loading

A UD-composite can be loaded along the fibre direction as well as in any direction at an angle to the fibre direction. Such off-axis loading will result in (very) low values for the stiffness and strength. Experimental data for the stiffness of cellulose fibre composites with PP matrix are shown in Fig. 13.

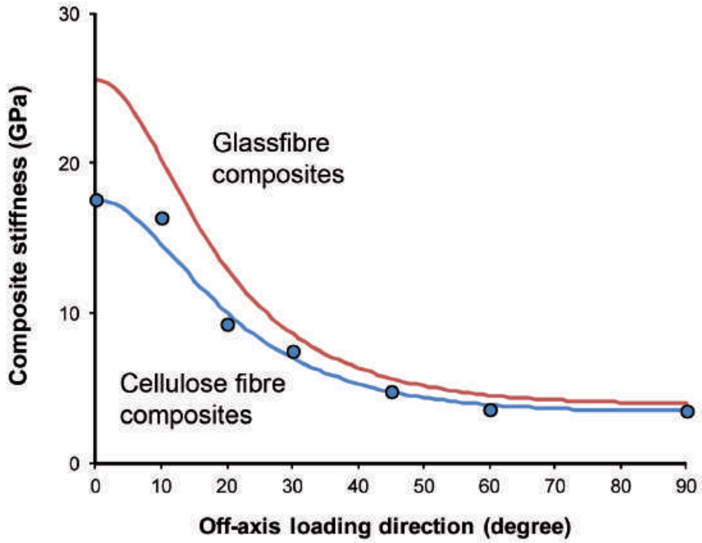


Figure 13: Experimental data points for tensile stiffness of composites of hemp fibres (with a volume fraction of 34%) in a thermoplastic matrix, loaded in directions from 0° to 90° relative to the fibre direction. The theoretical curve for these effects is calculated by using a cellulose fibre shear stiffness of 8 GPa. The corresponding curve for glass fibre composites is also shown, and illustrates that the two composite materials have low and similar tensile stiffness at large off-axis angles (more than about 30°).

10. Composite fracture energy

For composites with long parallel fibres, loaded along the fibre direction with a crack opening transverse to the fibre direction, as shown in Fig. 14, a calculation can be made of the energy consumed during this opening and advancement of the crack. During this process the fibres are pulling out of their respective "holes" in the matrix, as illustrated in Fig. 15, and this consumes (a large amount of) energy.

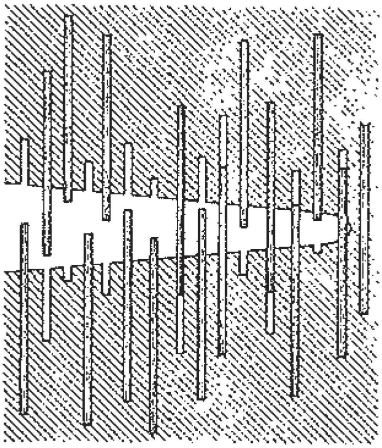


Figure 14: The composite with parallel fibres and a crack transverse to the fibre direction will show fibre failure on either side of the advancing crack. These fibres will be pulled out of the holes in the matrix. This pull-out process occurs against the adhesion and friction at the interface between fibre and matrix.

Figure 15: An example of the fracture of a composite with long parallel glass fibres in a polymer matrix. The micrograph shows the one side of the crack after the test specimen has separated into two parts. The fracture surface shows the fibres which have pulled out of the opposite side of the crack.

An example of the experimental values of the fracture energy for a composite, as compared to the fracture energy of the fibres and the matrix on their own, is shown here for data referring to glass fibres in an epoxy matrix:

Material	Fracture energy
Glass fibres	ca 10 J/m^2
Epoxy	100–300 J/m^2
Composite of glass fibres/epoxy	40,000–100,000 J/m^2

The fracture energies are given in units of Joule per square metre, and the very high values for the composite are based on the fibre/matrix interface and the fact that the fibres are pulling out of the matrix against adhesion and frictional sliding along the interface. These values illustrate that (often very) large fracture energies can be built into composites by tailoring the interface bonding and the fibre lengths. The fracture energy "translates" directly into the practical term *fracture toughness* (resistance to catastrophic failure).

The fracture energy of a composite depends on the fibre strength, the fibre volume fraction in the composite, and the fibre length and diameter, as well as the interface strength between fibre and matrix. A calculation of the fracture energy can be made for a model with fibres pulling out of the matrix, and the fracture energy for varying fibre lengths is shown in Fig. 16. It is noted that the fracture energy reaches a sharp maximum at the critical fibre length and that the fracture energy decreases markedly for long fibres.

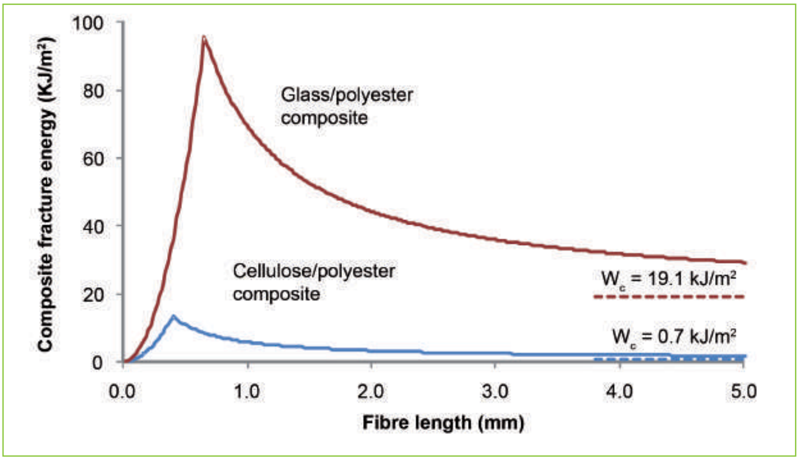


Figure 16: The calculated composite fracture energy as a function of fibre length (in mm). Cellulose fibre composites are compared with glass fibre composites. The dotted horizontal lines indicate the fracture energy value at infinite fibre length. The material values are: cellulose fibre stiffness 65 GPa, glass fibre stiffness 70 GPa, cellulose fibre strength 800 MPa, glass fibre strength 3500 MPa, cellulose/polymer interface strength 20 MPa, glass/polymer interface strength 40 MPa, cellulose fibre diameter 20 µm, glass fibre diameter 15 µm, composite fibre volume fraction 50%.

In evaluating the properties and in particular a profile of different properties for a given application, a compromise will often be needed between, for instance, strength and toughness. Most materials show either high strength or high toughness. Since composites to a large extent can be tailor-made to have a given property profile, it is also of interest to evaluate the possibilities for tailoring the toughness for fibre composites.

An important parameter for the fracture energy is the shear strength of the interface between fibre and matrix. This shear strength is based on the chemical and physical bonding, on the molecular level, between the fibre surface (cellulose of flax and hemp fibres) and the polymer matrix. Since the fibre cellulose surface is hydrophilic and the polymer matrix is often hydrophobic, the bonding will often be rather weak. This is a potential *advantage* for the fracture energy, which will increase when the interface shear strength decreases. But at the same time a low interface strength leads to inefficient use of (short) fibres for composite strength, as illustrated in Fig. 12. These two counteracting effects need often to be considered when tailoring composites with a specific property profile. The interface bonding between fibre cellulose surfaces and polymers can be modified, and especially improved, by various chemical treatments. By such treatments, additional chemical compounds are attached to the cellulose surface. This is done either "directly" by fibre surface treatments, or via addition of the chemical compound to the matrix polymer. One such chemical compound is maleic anhydride (MA). Composites made of hemp fibres and polypropylene matrix, with and without MA at the interface show different fracture behavior, as illustrated in Fig. 17, and also shown in Chapter 2, Fig. 18.

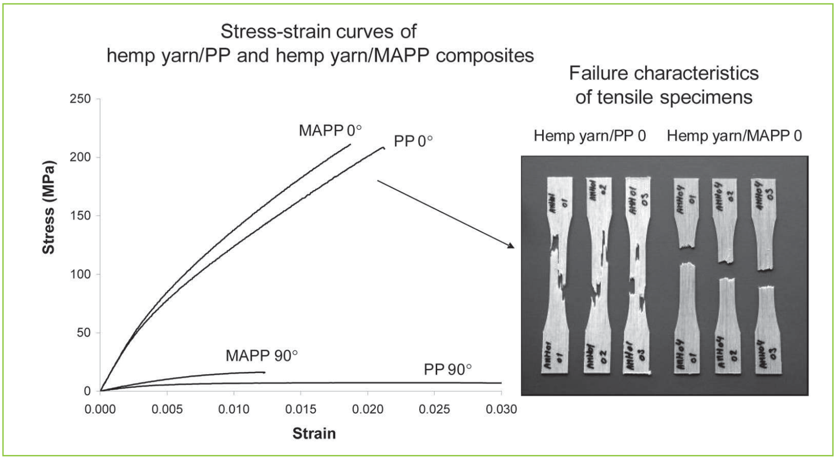


Figure 17: Composite samples of hemp fibres and polypropylene matrix. Without MA (samples called hemp yarn/PP) the strength at 90º is low and the fracture appearance shows a large and jagged fracture region along the fibres. With MA (samples called hemp yarn/MA-PP) the strength at 90º is higher and the fracture appearance has a smaller fracture region, transverse to the fibres. These observations indicate a rather low interface shear strength, with a lot of interface failure along the fibres, for composites without MA, and a rather higher interface shear strength for composites with MA.

11. Composites with porosity

Composites based on flax and hemp fibres can conveniently be fabricated from preforms with UD fibre arrangement or by filament winding of yarns into a UD arrangement, as illustrated in Fig. 18. Composites of cellulose fibres (flax and hemp) normally have some special characteristics, such as twisted fibres in the yarns, and porosity (voids) in the composites.

The porosity content is normally very small for low volume fractions of fibres, and can be rather large for high volume fractions of fibres, as illustrated in Fig. 19. The high (structural) porosity content at high fibre fractions is linked to the normally low packing ability of cellulose fibres. Porosity, in general, has a detrimental effect on composite mechanical properties.

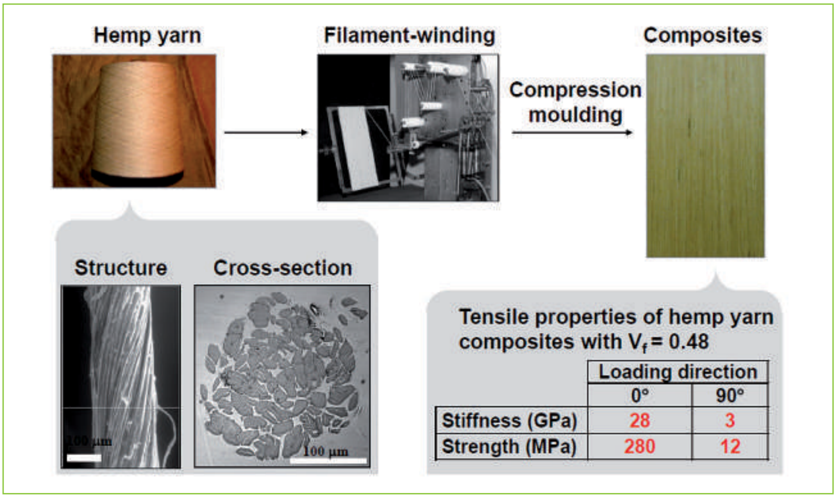


Figure 18: The fabrication of a UD composite by filament winding gives a high quality composite. The hemp yarns are normally twisted, and the composite can contain porosity.

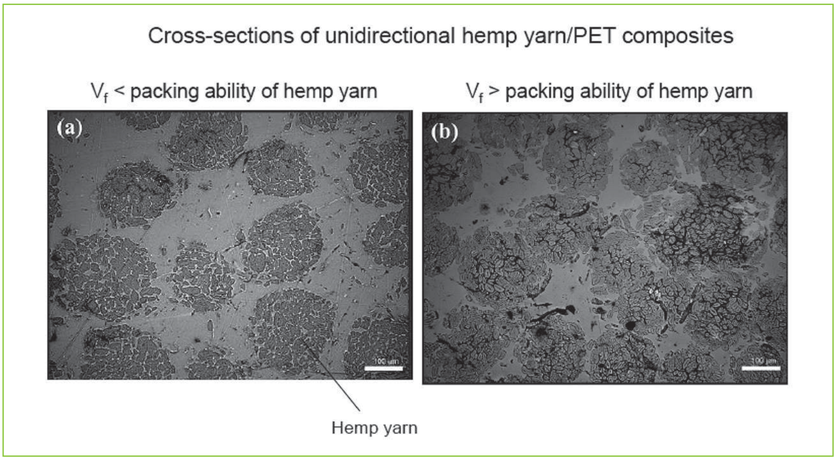


Figure 19: Hemp yarn composites normally have low porosity content at low fibre content, but can develop high porosity content at high fibre content.

A model has been established to describe the combined effect of (high) fibre volume fractions and (high) porosity fractions in composites. Based on the weight fraction composition of a composite, the *volume* fractions of fibre, matrix and porosity will follow curves as shown in Fig. 20.

The combined effect of increasing fibre fraction and the presence of (high) structural porosity content leads to a maximum in physical properties, such as density, and in mechanical properties, such as stiffness, as shown in Fig. 21 for the composites of Fig. 20.

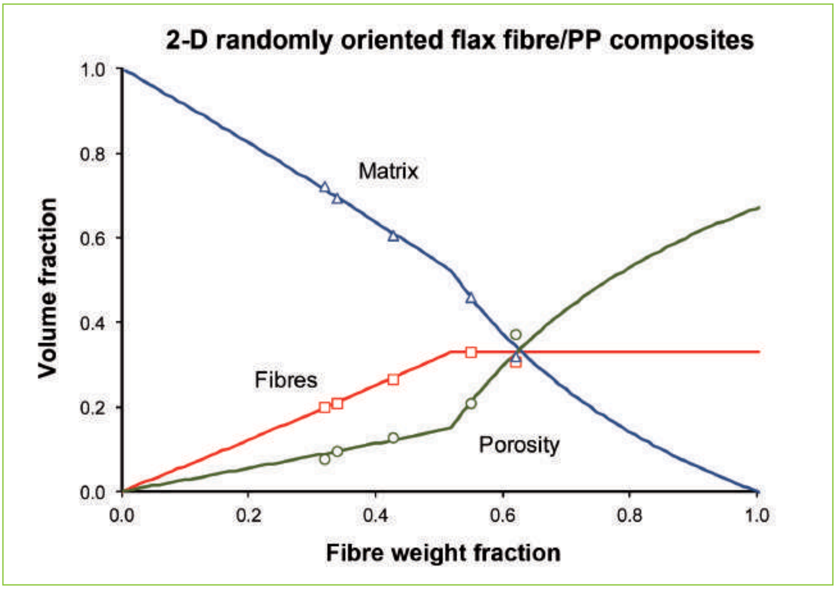


Figure 20: Calculated curves as a function of the weight fraction of flax fibres in a composite with polypropylene matrix. The curves represent the volume fractions of fibres, matrix and porosity, respectively. The data points indicate measured values for fibre, matrix and porosity volume fractions. At a transition weight fraction of 52%, the fibres are packed to their maximum, which means a maximum fibre volume fraction in the composite. At higher fibre weight fractions (and thus lower matrix weight fractions) there is not enough matrix to fill the open space between the fibres in the maximally packed fibre arrangement. This causes (structural) porosity, which can reach rather high values.

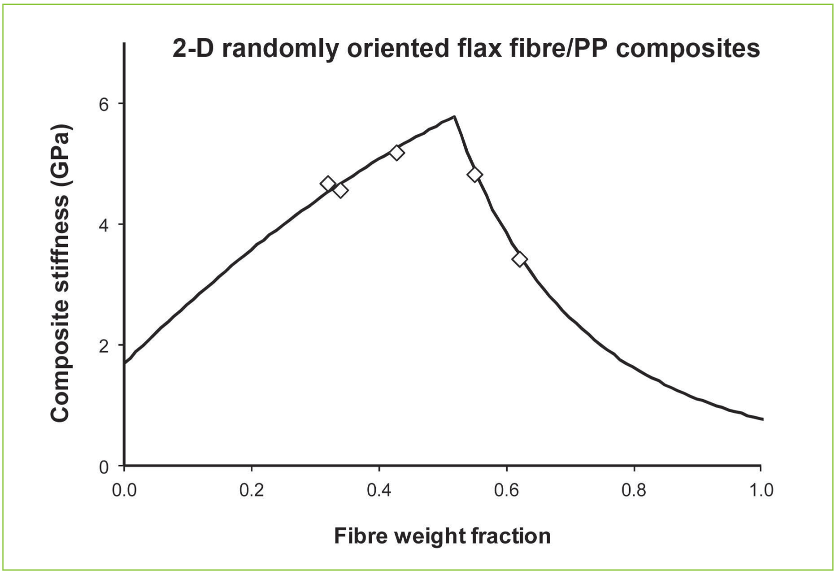


Figure 21: The composite stiffness for composites of flax fibres in a randomly oriented 2-D fibre arrangement (planar mat of fibres) in a polypropylene matrix. Composites with varying contents of fibres are shown. The calculated curve for stiffness shows the maximum, and the data points follow the curve. The transition fibre weight fraction is 52%, and this is the optimum fibre content for maximum stiffness for these flax/PP composites.

12. Optimal composites

On the basis of the fibres and the matrices, a wide range of composites can be designed. Some examples are listed in Table 4. The common assumption is that the composites contain aligned fibres (UD-arrangement) and that the volume fraction of fibres is the typical maximum which can be obtained in practice (often governed by the processing method used). This leads to the maximum obtainable properties, such as stiffness and strength.

- Table 4 -
Properties of optimal composites

	Cellulose/polymer	Glass/polymer	Carbon/polymer
Fibre weight fraction (%)	45	68	69
Fibre vol fraction (%)	40	50	60
Density (g/cm^3)	1.32	1.90	1.56
Stiffness (GPa)	26	36	181
Strength (MPa)	380	1,800	1,500
Stiffness/Density	21	19	116
Strength/Density	280	950	960

These (typical) data indicate the *maximum* potential, and shows that the cellulose, i.e. flax and hemp, fibres can deliver composites with stiffness/density ratios which can compete with glass fibre composites. On the strength issue, the cellulose fibres are (still) of rather low strength, as discussed above, and improvements are needed.

13. Practical composites

The cellulose (and other) fibres used for fabrication of composites are often supplied as preforms. These preforms have different, often commercial, names. A detailed description of fibre preforms is given in chapters 3 and 5. The preforms normally aim to ensure certain fibre arrangements and fibre directions, in order to lead to composites with special directional properties.

A range of experimental data collected for various composites and composite compositions are shown in Table 5, for cellulose fibre composites as compared to glass fibre composites. The composites are characterized by fibre fraction, by fibre preform type, and by fibre orientation (RD = random, UD = aligned). The stiffness and strength values are plotted in Fig. 22. The curves show the linear dependence for stiffness and for strength on fibre volume fraction and also show the importance of fibre orientation; the data for stiffness are more clearly linear than the data for strength.

- Table 5 -
Properties of practical composites

Composite Fibre/matrix	Fibre volume fraction %	Stiffness GPa	Strength MPa
Flax/starch – loose fibres, RD	37	8.3	51
Jute/PP – non-woven mat, RD	32	8.4	39
Jute/PP – non-woven mat, RD	30	5.2	40
Flax/epoxy – yarn, UD	40	28.0	133
Flax/PP – yarn, UD	55	28.2	321
Flax/PLA – non-crimp fabric, UD	39	19.5	150
Flax/epoxy – non-crimp fabric, UD	35	19.8	234
Glass/PP – loose fibres, RD	30	7.3	100
Glass/PP – chopped strand mat, RD	20	5.4	77
Glass/PP – roving, UD	60	45.0	1,020
Glass/epoxy – roving, UD	55	39.0	1,080

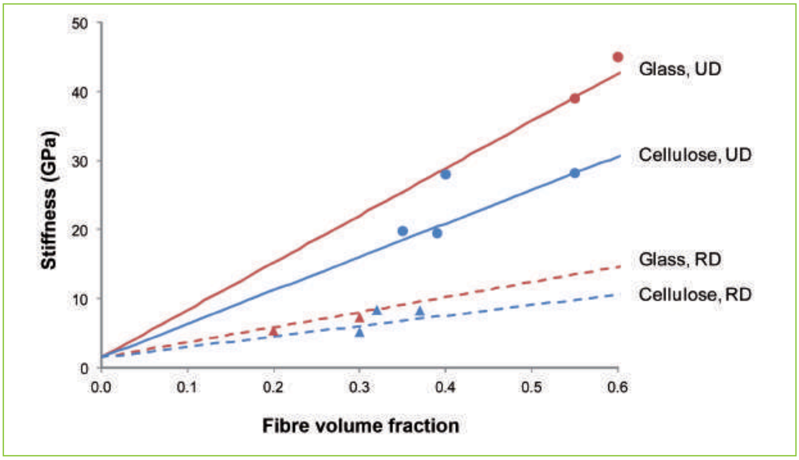


Figure 22a: Experimental data for stiffness for a range of cellulose fibre composites and glass fibre composites. The stiffness values are plotted as a function of fibre volume fraction; fibre orientation is marked by RD = random, and UD = aligned. The curves are fitted to the experimental data, and the curves for the UD-composites follow the basic curves of Fig. 5a.

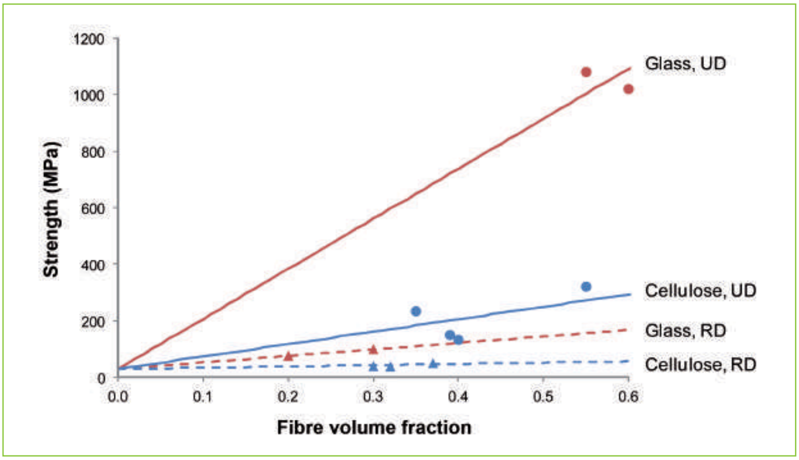


Figure 22b: Experimental data for strength for a range of cellulose fibre composites and glass fibre composites. The strength values are plotted as a function of fibre volume fraction; fibre orientation is marked by RD = random, and UD = aligned. The curves are fitted to the experimental data, and the curves for the UD composites are below the basic curves of Fig. 5b.

The different preforms have different packing ability due to the different fibre directions in the preforms. The multidirectional fibre arrangements such as 2-dimensional mats, can be packed less closely than preforms with mainly or only UD fibre arrangements. This implies that the maximum fibre volume fraction (at the transition fibre weight fraction, see section "Composites with porosity") will be smaller for mats than for UD preforms. The practical range of fibre volume fractions for the different preforms in composites is illustrated in Fig. 23, for cellulose fibre composites and for glass fibre composites.

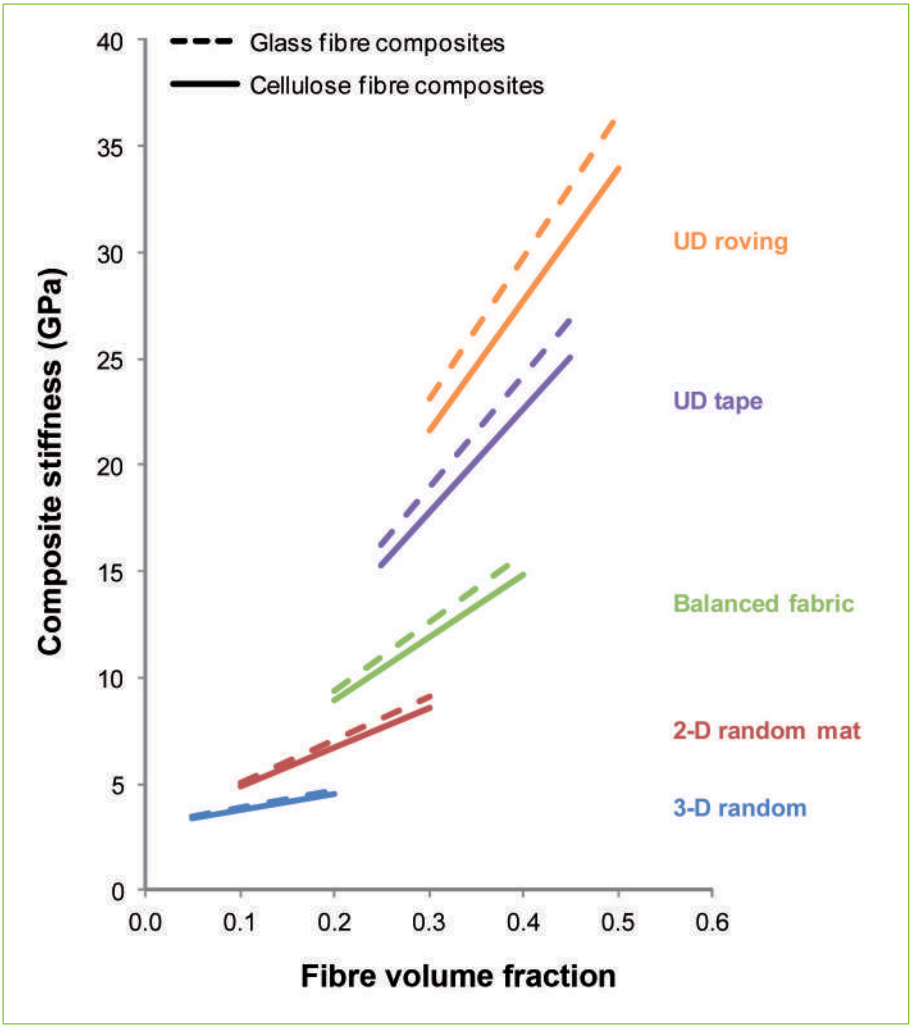


Figure 23a: The practical composite stiffness as a function of fibre volume fraction for various fibre preforms, available for fabrication of composites. The preforms are indicated and marked with colour. The practical range, in terms of fibre volume fraction, is indicated by the length of the lines. Cellulose fibre composites (full lines) are compared with glass fibre composites (dotted lines). The material values are: cellulose fibre stiffness 65 GPa, glass fibre stiffness 70 GPa, polymer matrix stiffness 3 GPa.

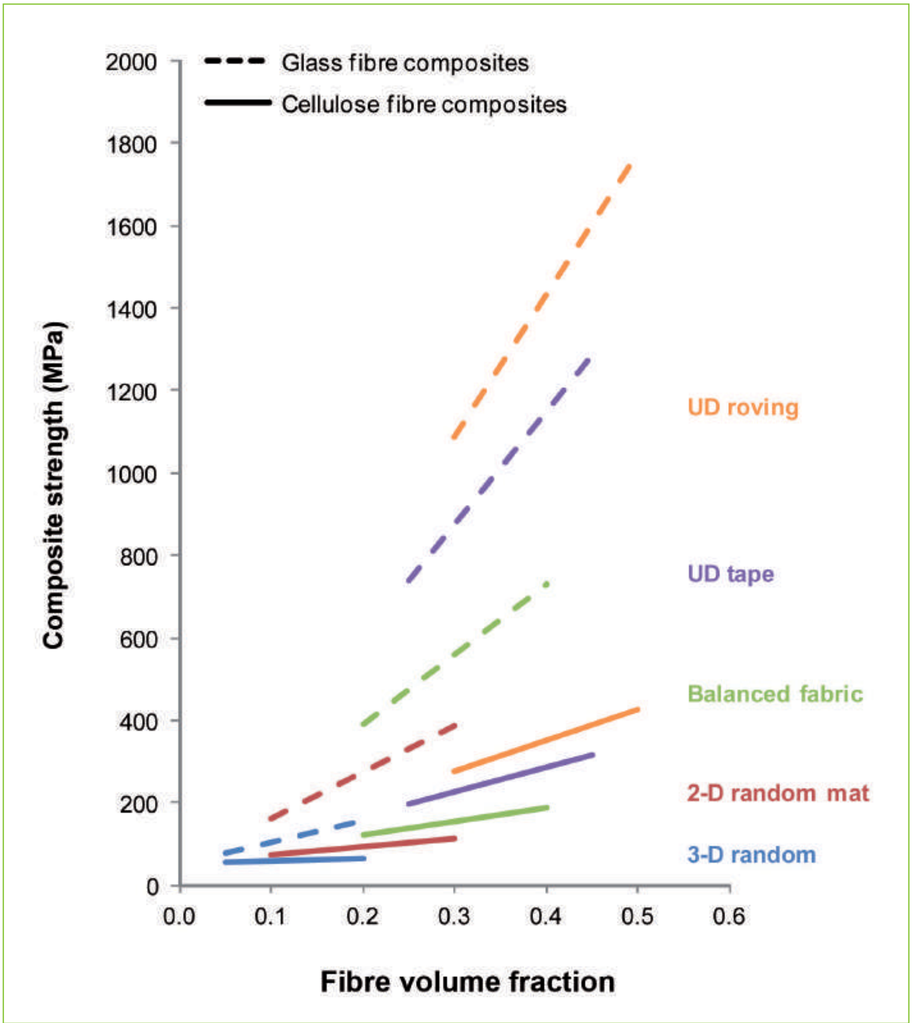


Figure 23b: The practical composite strength as a function of fibre volume fraction for various fibre preforms, available for fabrication of composites. The preforms are indicated and marked with colour. The practical range, in terms of fibre volume fraction, is indicated by the length of the lines. Cellulose fibre composites (full lines) are compared with glass fibre composites (dotted lines). The material values are: cellulose fibre strength 800 MPa, glass fibre strength 3500 MPa, polymer matrix strength 50 MPa.

14. Technical and environmental aspects

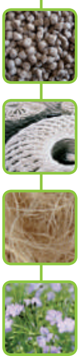
A range of technical issues and environmental issues can be handled (only) in a qualitative way, and some of these are presented in Fig. 24.

Properties	Plant fibres	Synthetic fibres
Technical		
Density	Low	Moderate
Mechanical properties	Moderate	High
Moisture sensitivity	High	Low
Thermal sensitivity	High	Low
Environmental		
Production, energy	Low	High
Resource, sustainability	Infinite	Limited
Health aspects	Good	Moderate
Recyclability	Good	Moderate

Figure 24: The cellulose fibres from plants have potential for structural applications on the basis of their technical properties, and they have the special additional potential of being attractive on the basis of their environmental aspects.

15. Concluding remarks

This chapter has treated central mechanical, physical and chemical properties of cellulose fibre composites with special focus on fibres from flax and hemp plants.
Composites properties such as stiffness, strength, toughness, density and moisture absorption are adressed.
Basic and simple ways of calculating these composite properties are shown and desmonstrated with data and curves.
The effect of porosity in composites on the properties and performance is emphasized and discussed.
Composites with optimal properties are presented, and these are compared to practical composites and their properties and performance.
Technical and evironmental aspects are briefly compared and contrasted.



- VIII - Flax & hemp composite applications

TECHNICAL SECTION OF CELC

In collaboration with
Moussa GOMINA,
Research Scientist, CRISMAT laboratory,
CNRS at ENSICAEN, France.

1. Automotive

The automotive market is undergoing massive changes. Under growing pressure from environmental regulations, builders are tightening specifications for their equipment manufacturers. To reduce CO_2 emissions and shrink the environmental footprint of transportation, the market is demanding more lightweight materials that are recyclable at end of life.

European directive
One objective set by the European 2000/53 directive is to be recycling 85% and reusing 95% of automotive components by 2015.
The European Commission Regulation No.725/2011 will allow the automotive industry to benefit from carbon credits if it invests in new technologies to reduce CO_2 emissions on new cars. From now until 2015, CO_2 emissions for new cars registered within the EU must be gradually reduced to a maximum 130 g/km (versus an average 140 g/km in 2010), subject to a fine for each registered vehicle.

Flax and hemp reinforced composites can help to meet these new requirements, and have special appeal for builders. As a side note, Henry Ford designed the first hemp-reinforced car in 1941 so that his vehicle would weigh less than those of his competitors. His car in fact weighed only 1,043 kg, or a third as much as the competing steel-clad vehicles at the time.
The low weight of flax and hemp is a determining factor in optimising energy consumption during the parts production process, and provides attractive energy savings during use as well.

While biocomposites currently make up 5-20 kg of the total weight of a vehicle, as a function of the brand name and model, flax and hemp fibres account for only 1 kg of that. Injected plastic parts made with natural fibre reinforcement account for less than 1% of French automotive parts production, which leaves quite a lot of room for development.

Thanks to their properties, flax and hemp fibres can meet all of builders' specification requirements:

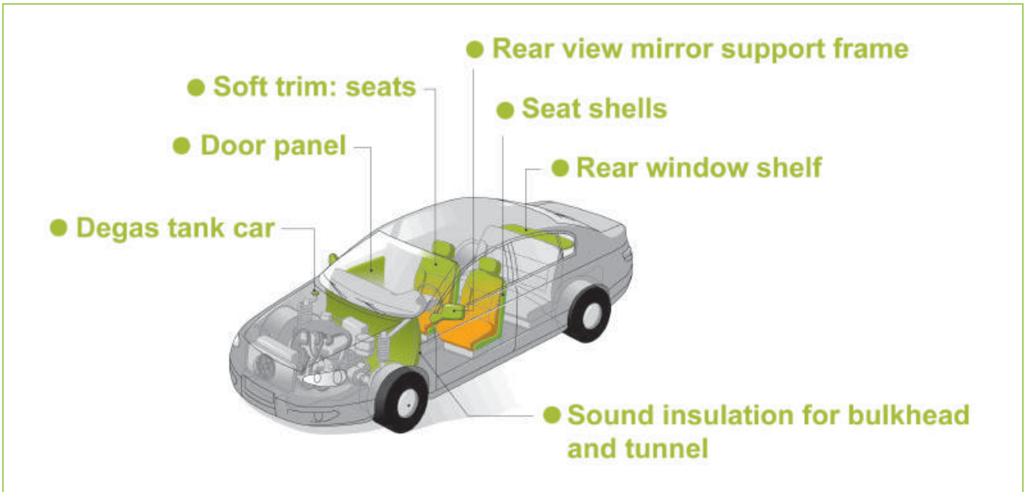
- CO_2 storage – biomass production
- lighter products (density of flax and hemp fibre is 1-1.5 kg/dm^3, compared to 2.54 for glass fibre)
- good breaking, compression and torsional strength
- non-abrasive
- won't lead to injury if broken
- odourless

The micro-structural morphology and high modulus of elasticity of the hollow natural fibres impart good sound and vibration damping properties. The fibres can absorb vibrations without deterioration of their mechanical properties, and their morphology also attenuates noise, giving good acoustic comfort.

The type of parts that are either already being produced or under development are:

- hidden interior parts such as door panels, rear seat shells, sound insulation for bulkheads, rear window shelves, and dashboards;

- structural parts such as floors, under-the-hood parts, degas tank caps, air ducts for centre and side ventilators, and rear-view mirror support frames.

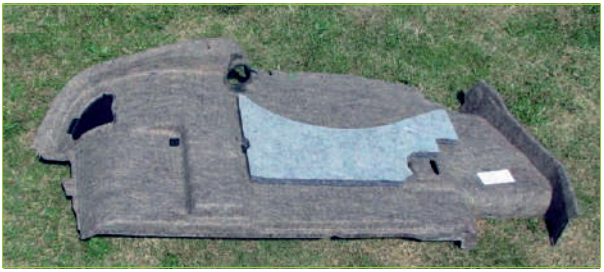


Source: *PSA*

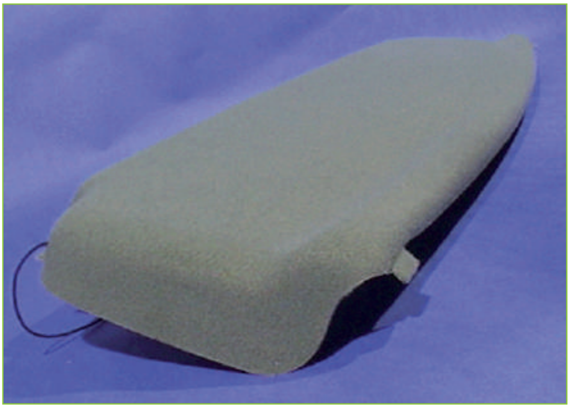
Thermo-compression moulding, non-woven mat in 50% flax/recycled or virgin PP

Source: *Ecotechnilin*

- Wheel housing or side trunk lining



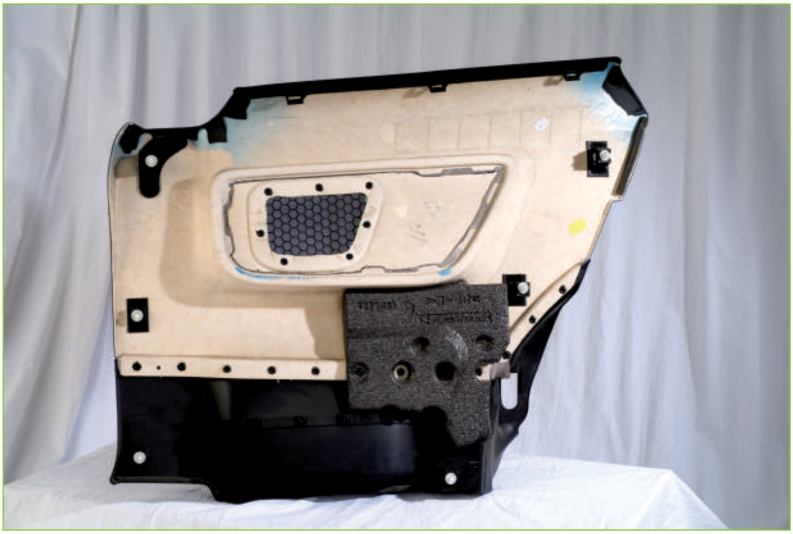
- Rear shell for front seat



- Rear window shelf

- Dashboard

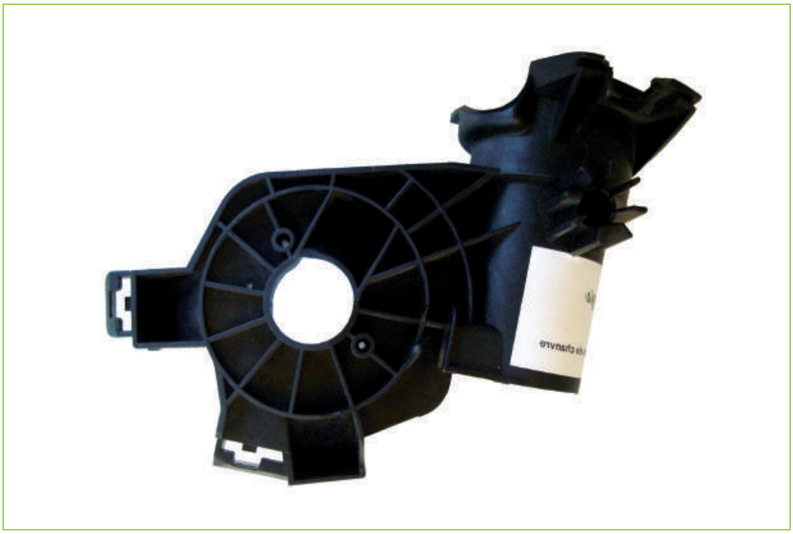
- Door insert



Injection of thermoplastic compounds

Flax and hemp fibres give composite parts high deformation strength when exposed to heat (under 200°C).
Given the working conditions in the automotive industry (alternating stresses and temperature), the injection-moulded parts used for the engine compartment and accessories are mostly made of fibre-reinforced polymers (in descending order of use: PP, PA and other engineering plastics). Below, several examples are presented of injection moulded parts made of thermoplastic composites reinforced with (short) flax or hemp fibres.

- Rear-view mirror support frame



Source: *AFT Plasturgie*

• Coolant degas tank cap

Source: *PSA*

Source: *AFT Plasturgie*

For example, a composite with PP copolymer matrix reinforced with 30% 4-mm hemp fibres has a number of significant advantages:

- high precision and dimensional stability,
- compliance with specifications for an exterior part,
- a manufacturing process that consumes 43% less water and reduces greenhouse gas emissions by more than 14%,
- a rear-view mirror that weighs only 128 gr compared to 136 gr for the equivalent glass-fibre-reinforced part (a 5% weight reduction),
- 25% less consumption of non-renewable resources as shown by life cycle analyses.

- Glass run channels and weatherstrips

These parts are made of extruded hemp fibre/PP composite. As a functional component, a weatherstrip must be perfectly waterproof, airtight, noise proof and odourless. As a structural component, it must be stiff, durable, and moisture proof.

Hemp fibres meet these specifications, thanks to their:
- bending strength,
- adaptability to heat cycles (vapour absorbing).

2. Mobility and transport

Globally, the mobility sector is the largest application sector for technical textiles in terms of value. In Europe, it is the leading sector in terms of volume and price.

By 2015, just like regular cars, motorised conveyances like scooters, electric cars and light vehicles will have to comply with European Directive 2000/53, which requires recycling 85% of end-of-life car components and recovering 95%.

In these ecological times, biodegradability and recyclability are becoming priorities that must be taken into account in the design of parts, so flax and hemp fibres will inevitably develop over the short term.

Their natural properties match up with the requirements of manufacturers:
- low weight, giving a final product that is lighter than one using glass fibre and which therefore consumes less energy;
- good breaking, compression, and tensile strength;
- noise and vibration damping for the same mechanical strength, due to their modulus of elasticity and hollow structure, and therefore better acoustic comfort.

Three-wheeled scooter

This prototype scooter is an eco-designed, three-wheeled electric vehicle that can carry one person plus objects (a load up to 110 kg up front or in rear wheel drive). Its body is made of a polyester matrix reinforced with a technical flax (non-twist) woven roving (50% by weight).

Due to the scooter's compact size, it can be placed in the trunk of a car.

Source: *Dehondt Groupe*

Source: *Citi Technologies*

Electric scooter

Another prototype for a 125 cm^3 electric scooter was developed using only fifteen parts for the structure and the trim panels, compared to the fifty parts required for a standard scooter. Besides facilitating the construction, using fewer parts also reduces the vehicle weight by about 20%. The body consists of two structural half-shells made of flax fibre/tannin resin composite, and the suspension link is also reinforced with flax fibre.

Concept car

Source: *Huntsman Advanced Materials Gmbh*

This van prototype is designed for urban deliveries.

Its frame is made of a 300 g/m^2 plain-weave flax fabric sized with epoxy resin.
The semi-structural body parts are either one-piece parts (3 mm thick) or cork-cored sandwich parts with 3-mm-thick skins. All of these components were made using an infusion process.

The fibre content in the one-piece parts and the sandwich skins is 35% by volume.
Besides playing a semi-structural role, the flax-composite body parts also contribute to the vehicle design by giving a "natural fabric" look that is emphasised by the resin's special white colour.

- Table -
Thermo-mechanical properties demonstrating the structural role of flax reinforced composite

	Standard	Measured Value
Heat Deflection Temperature	ISO 75-3	**86°C**
Tensile Strength	ISO 524-4	**128 MPa**
Flexural Strength	ISO 14125	**160 MPa**
Flexural Modulus	ISO 14125	**10.7 GPa**
Impact Resistance (Barcol Hardness)	ISO 868	**80**

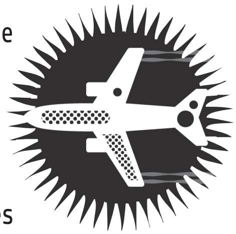
(Based on one-piece samples, 2 mm thick with 35% fibre by volume)

Heavy-duty vehicles

For the moment, no regulations exist with respect to recycling for heavy-duty vehicles like lorries and coaches.

Seeking to improve vehicle efficiency and thereby reduce fuel costs, builders are testing the incorporation of natural fibres into body parts, in particular to optimise vehicle weight reduction.

3. Perspectives / Aerospace



Due to aluminium shortages during World War II, the British built the fuselage of their Spitfire aircraft from a flax-fibre-reinforced phenolic resin composite. In the early 1940s, that composite material (called Gordon Aerolite) was being used for the linkage assembly on the Royal Air Force's Miles Magister trainer aircraft.

Today, the aerospace sector already accounts for 4% of the composites market, and specialists are forecasting an 11% increase or more by 2014. The aerospace sector, which has very high standards when it comes to testing the reliability of its materials, is taking an interest in flax fibre composites. These new-generation materials are currently included in aerospace research and development programmes, but before being definitively incorporated into aircraft construction, they need to be tested over a period of at least ten years.

The aerospace sector is still one of the most promising ones. Because the industry is dependent on the upward fluctuations in oil prices (and even the risk of fossil fuel shortages), builders are turning to alternative resources in order to design aircraft from lightweight materials that are reliable and more environment friendly.

The International Air Transport Association (IATA) has made the commitment to stabilise CO_2 emissions by 2020, and cut them in half by 2050, taking the 2005 levels as a baseline. Lowering the weight of aircraft is a way to reduce their emissions.

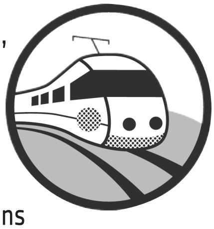
Passenger safety regulations are extremely strict. Flax fibres have potential safety advantages for use in cabin components such as doors for baggage compartments, etc., because they are stiff, lightweight and non-abrasive during implementation, and they present no risk of cutting anyone if they break.

Flax fibres used in conjunction with another suitable reinforcement like carbon fibres offer high resistance to mechanical stress.

Thanks to the low weight of flax fibres, flax/epoxy composites weigh less than glass/ epoxy composites for the same reinforcement content and hence similar stiffness, leading to significant fuel savings.

Overall, flax fibre composites used inside aircraft cabins have greater bending stiffness than glass fibre composites for the same mass per unit area.

4. Prospects / Railway



In the current context of congested roads and growing air pollution, the railway sector's major priorities are to enable their passengers to travel safely in comfort and to optimise environmental protection. Developing cross-border high speed trains is the ideal response to these contemporary issues.

The railway sector has potential: the time is ripe to develop high-speed trains designed entirely to fill the needs of an international market in compliance with technical specifications for interoperability (TSI).
That sector is also rallying to take environmental concerns into account. Beyond issues like component recyclability or biodegradability, specifiers are concerned with producing lighter railway vehicles not only to achieve higher speeds and optimum energy savings, but also to decrease braking time in order to optimise the number of trains circulating. Another consideration is that operators pay fees that are indexed on the vehicle weight. In this context, flax and hemp offer definite advantages, thanks to their good mechanical properties.

The new public transport fire safety regulations also represent a challenge for composite manufacturers. Phenolic resin matrix composites are among the more promising materials, because they are inherently fire resistant, and also emit very little gas or smoke.

The objective is to reduce energy consumption by more than 15% compared with competing materials, and to propose components that are up to 98% recyclable. Flax fibre is being tested with a 100% bio-sourced matrix in semi-structural interior trim parts, such as luggage racks.

5. Sports and leisure

Applications using thermoplastic and thermoset composites reinforced with flax and hemp fibres are both environment friendly and technical, so there could be significant market potential in the sports and leisure sector.
At present, although flax fibre can be used either alone or in combination with carbon fibres in thermoset resins to produce structural parts (frames or hulls in the sports sector) and the advantages have already been amply demonstrated, only 8% of annual flax-fibre production is used in composites.

Their low density and mechanical properties are a guarantee of:

- a lightweight, finer product
- better manoeuvrability
- good breaking, compression and torsional strength, which is crucial in applications requiring optimum user protection to minimise the risk of injury

Their stiffness (equivalent to that of glass fibre and one-third that of carbon fibres) allows:

- hybrid flax/carbon products that are almost as stiff as all-carbon products
- much higher specific stiffness than sports products made of glass-fibre composite

The fibres' hollow structure plus their high elasticity modulus confer high noise and vibration damping properties, meaning comfortable use and fewer muscular injuries.

Tennis & padel racquets

Tennis is the leading individual sport, with more than 50 million players worldwide, so this is a major sector. Whether or not they are professionals, players seek out technical equipment that enables them to maximise their performance and lower the risk of muscular injury.

The flax is incorporated into the frame as drape-formed plies of flax/epoxy and carbon/epoxy prepregs. Thanks to the vibration-damping properties of flax fibre, a flax content of 8% to 25% gives effective results that reduce the risk of tennis elbow. A racquet incorporating 15% flax content improves the damping factor by 22%.

So far, seven different tennis racquet models for regular to intensive practice are on the market.

Source: *Artengo*

Fishing poles

Fishermen want poles that are ideally stiff, yet with enough manoeuvrability to avoid hurting the back or arm.

As with the tennis racquet, the flax incorporated into the structure as drape-formed plies of flax/epoxy and carbon/epoxy prepregs provides better vibration damping and thus less risk of muscular injury. Its low weight ensures better manoeuvrability.

Source: *Caperlan*

Surfboards

Low weight and feel are essential for successful surfing, because the surfer becomes "one" with his surfboard. Several different models fabricated with different processes are being tested or are already on the market.
One pioneering board incorporates a sized flax fabric reinforcement into epoxy resin using a vacuum lay-up process. This technique produces lighter, more easily handled boards with better vibration damping, and therefore significantly less risk of muscular injury (arms, back).

Source: *Sun-7*

One prototype already tested in competition is a sandwich board with outer plies of flax/greenpoxy composite and a recyclable polystyrene core. Besides offering low weight and manoeuvrability, the fibres proved to be waterproof when tested in real life conditions. From the environmental point of view, the board manufacturing process requires 5-10 times less energy than a fibreglass model.

Another type of surfboard has been on the market since the summer of 2010. The construction technology used for the board involves vacuum lay-up of a paperboard honeycomb and an ecodesign approach: the usual polyurethane is replaced by a block of recycled polystyrene foam that is guaranteed to be hydrochlorofluorocarbon free. To lower the weight but maintain the sturdiness and flexibility, quadriaxial flax fibre reinforcement is used instead of glass fibre, with a bio-sourced high-performance epoxy resin matrix.

Source: *Notox*

Skis


Source: *Wedze*

For downhill skis, using 20% flax fibre reinforcement in combination with glass fibre in an epoxy resin offers better vibration damping than other fibres. This makes the skis more comfortable on snow, especially hard snow. You get better cornering with less strain on the muscles, because the ski is easier to handle.


Source: *Rossignol*

Laminate moulding is used, with a multiaxial flax fibre reinforcement and TS polyurethane (PUR) injection. This technique produces a high-quality product through a controlled HQE (High Quality Environment standard) production process in an ISO 9001/4 certified plant.

Racing bike


Source: *Museeuw Bikes*

Aerodynamism and low weight are two key criteria for a cyclist, who must become "one" with the bicycle to save another second or two in time.

Replacing from 20 to 80% of the carbon by flax (lighter than carbon) in certain parts of a bicycle frame is a first, because the flax fibre is used as structural reinforcement. Tests during an 80-km race lasting two hours and fifty minutes demonstrated that there were 20% fewer vibrations for this particular bicycle, which is for semi-professional or professional use.

This constitutes a significant reduction, and is the result of the flax fibre's absorption capacity. The risk of muscular injury is minimised without sacrificing any of the bicycle's stiffness or sturdiness, and the bicycle also has greater breaking, compression and torsional strength.

Mountain bike helmet


Source: *Urge bike*

It is already possible to develop leading-edge recreational products where biomaterials can provide superior technical characteristics. We can also consider the mass production of mass consumption products in different versions, e.g. helmets and other personal protection equipment.
Helmets with a structure made of a vinylester/PE matrix reinforced with flax prepreg fabric not only protect the head and absorb impacts, but are also more comfortable due to the use of lightweight flax fibre. At 966 grams, this type of helmet weighs less than a fibreglass helmet (995-1050 g). The helmets are also better ventilated, thanks to the capacity of natural cellulose fibres to absorb moisture, which helps to regulate the micro-environment between helmet and skin more efficiently.

Prospects

The sports and leisure sector conveys a highly positive image for biomaterials, as these are incorporated into high-quality, ultra-engineered products. Also, with the reduced risk of injury, irritation or allergies, natural fibres benefit from a "healthy" image.
The recyclability of engineered fabrics impregnated with thermoset resins is still an issue that hinders mass production. The significant research advances made in that sector should soon remove that obstacle.

6. Boating

Currently eight out of ten leisure craft are made of composite materials. This creates end-of-life issues, because the waste is difficult to recycle. France is the world's second-largest player in the boatbuilding market for this type of craft. The market is growing 20% per year – so the stakes are high for natural fibres. Flax and hemp fibres are both environment-friendly and technical, and their mechanical properties make them suitable for use in structural parts like hulls.

Flax could account for a significant share in boating composites, up to 30% of the market in replacement of glass fibre.
Due to its inherent properties, flax fibre is a high-value-added material for the sector's specialists, since its low density imparts:

- low weight for the finished product,
- greater manoeuvrability,
- good breaking, compression and torsional strength.

The hollow fibres are vibration damping (extremely important at sea), considerably increasing the boat's gliding capability and reducing impact injuries for skippers.

Racing sailboats

Source: *Huntsman Advanced Materials GmbH - © F. Reinhart*

There are more and more prototypes for sailboats made of flax fibre reinforced composites, since they are highly appreciated for their lightness, manoeuvrability, glidability and environment friendliness.

The pioneer turns out to be one of the ten most high-performance models in the 6.50 yacht racing sector. Its main added value is the low weight: 50% of the total reinforcement fibre weight consists of flax. For the hull and deck, about 80% of the fibres used are flax, making the boat one of the lightest in its category at 750 kg.

The hull and deck include composite parts that are 100% flax fibre reinforced, processed in the form of unidirectional prepreg tapes (180 g/m^2) that are sized for maximum compatibility with the epoxy resins used. The flax composite parts were assembled using UD or 2D carbon tapes laminated with an epoxy system.

The infusion-moulded composite materials are sandwich structures with a Styrene-Acrylonitile (SAN) foam core (density: 80 kg/dm^3) and skins with a 35% flax fibre volume content.

This racing boat has already participated in a number of races and regattas in which it has proved itself to be reliable.

Sea kayak

The first polyester/flax kayak prototype has been built and tested.

The initial tests showed promising results, and the flax fibre adds extra comfort: the kayak is lighter and easier to handle, adheres better to the water surface and has good hydrophobic characteristics. Due to its good impact resistance, kayakers suffer fewer muscular injuries.

Source: *Plasmor*

More trials are ongoing to substitute a biopolymer (PLA) for the polyester resin. Studies on the recyclability of the biocomposites and on load transfer mechanisms between flax fibre and the PLA matrix are showing promise. Various industrial tools for heat moulding were also tested. The prototype that was made consists uniquely of bio-based materials that are recyclable and compostable at end of life.

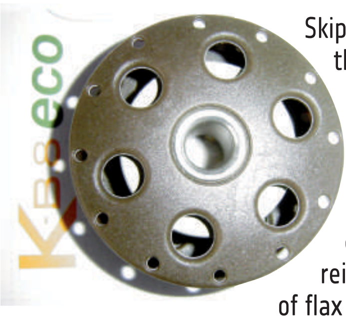
Sailboat

Source: *La gazelle des sables – JF Coudreau*

For pleasure boating enthusiasts, a small sailboat incorporating flax fibre has been marketed since 2005. A closed-mould vacuum injection process is used with polyester resin (RTM eco) to impregnate the reinforcement. This process has a number of advantages:

- fewer harmful emissions during fabrication,
- burnable end-of-life polymerised waste,
- biodegradable waste from plant raw materials, and especially
- reliable construction, with a nearly 0% residual bubble content.

Superstructure



Source: *Karver*

Skippers have two main requirements: lowering the weight of the boat, and obtaining parts that are very easy to manoeuvre. Superstructure fittings are key parts. Incorporating flax fibres is a solution that provides featherweight yet ultra strong fittings.

A French equipment supplier currently manufactures an environment-friendly pulley for which the flanges are flax fibre reinforced. These parts are obtained by injecting 15% by weight of flax fibre aggregate into a 100% biosourced PA11 (castor bean oil).

7. Packaging

Plastics currently account for more than 40% of the packaging sector, compared to barely 1% for biomaterials. Current regulations require the recycling of at least 72% of household packaging materials.

These new-generation materials have a number of advantages, including low weight and good mechanical strength even in thin layers. The use of hollow fibres like flax and hemp help to absorb moisture, which is a significant advantage in the food sector.

Smartphone shell

This niche packaging market is an ideal showcase for promoting the use of fibres in surface finishes. The shell's inherent strength, low weight and natural appearance make it an object that is perfectly in tune with consumer expectations in terms of efficient protection for their cell phones.


Source: *FiberShell*

The shell is made of a composite with a polyamide matrix reinforced with 50%+ flax fibre. It is ultra-light (7 g), ultra-thin (0.8 mm), and impact resistant. Several plies of fabric are used to reach the desired thickness and strength. The impregnated fabric is induction heated in a mould and then cooled. The shell is then precision trimmed, finished and hand polished.

Household packaging

The barely emergent packaging market is very buoyant, and is adapting slowly as a function of the stringent European regulations (1935/2004/EC) on anything to do with the food industry. The new regulation on plastics, called the PIM (for Plastic Implementing Measures), is due to replace the 2002/72 Directive and its various amendments, and should be a further boost to this highly promising sector.
Ongoing tests show that biomaterials are compatible with food. Research specialists say that it will soon be possible to put natural fibres on the list of food-compatible materials, just like wood flour and fibre, since the last obstacles – traceability, odour, and colouring – have been removed or are about to be.
Cost minimisation for polypropylene or polyethylene plastics could be achieved rapidly, both through compliance with the law and the recyclability obligation (and therefore removal of taxes and fines) and through the gains from local production: 40-60% of plastic bags are currently imported from Asia.

Cosmetics

Packaging for personal care products, cosmetics, and pharmaceutics is made by compounding PP/flax fibre (30%) composites. The flax is visible at the surface of the packaging, adding shelf appeal and giving a strong marketing pitch for products that are positioned as healthful and natural.


Source: *Aveda*

Shipping packaging

There are applications for biocomposites in engineered packaging for industrial use, notably in the logistics and transport sector. Biocomposites have advantages in terms of cost and reutilisation, and are a good alternative for wood pallets, for example.

The water-absorption capacity of natural fibres allows using liquid fillers when the fibres are mixed with a polymer. A part with 30% natural-fibre reinforcement can absorb up to 7% liquid when immerged. The liquid will then be released in standard temperature and relative humidity conditions. Handling pallets made of HDPE reinforced with 20% hemp fibre can absorb a germicidal solution in a few hours, then release it over a period of eight months or more. There are many prospects in the materials handling/packaging sector, especially the pharmaceutical and agri-food industries.

Technical advantages: robustness/impact resistance, moisture "reversibility", resistance to mildew, acids, fats and chemicals, safe for operators, weight savings, and easy handling.

A number of biocomposite properties can be exploited in engineered packaging for industrial use, especially in the logistics/transportation sector, e.g. the cost and reutilisation advantages of multi-packs for putting orders together.

According to French energy conservation agency ADEME[1], the plastic pallet and box market could reach 57 metric kilotons (KT) (4.1% of the total market) by 2015 and exceed 110 KT (6.7%) by 2030.

Prospects

Source: Egon Heger

While the packaging market for natural fibres is still relatively inconsequential, it is growing rapidly, because the packaging industry is subject to heavy pressure due to the Grenelle Environment Forum commitments and customer requirements. Packaging is regularly picked out as the main source of heavy waste production.

8. Convenience goods

Flax is especially known in the textile sector, where it is often in the forefront. In the convenience goods sector, however, its use in the form of composites is still very limited.

Flax properties enable:
- a smaller environmental footprint (see chapter 10)
- energy savings

1 Agence de l'Environnement et de la Maîtrise de l'Energie

While convenience goods might appear to be only a niche market for flax, the sector is turning out to be an attractive vehicle for communication as an ideal means to publicise the appeal of composites for everyday tools and accessories.

Now that consumers are aware of the need for environmental protection, they are able to appreciate that flax is a renewable, recyclable resource which helps to reduce the need to use fossil-fuel raw materials.

Horticulture

Demand is growing for applications for flower pots, racks, or stakes, e.g. recyclable or biodegradable pots. Surveys show that demand is high for decorative pots, due to the trend for sprucing up balconies and terraces.

Biomaterials like flax and hemp have their appeal in that market, because of their:
- low weight (a significant advantage for shipping and handling),
- durability,
- freeze-thaw resistance,
- similar or even lower cost compared to products made of traditional materials like wood, stone or terra cotta.

Source: *Az&mut © Morgane Le Gall*

The technique differs for thermosets and thermoplastics:

TS matrix – drape forming of a multiaxial flax/PE fabric

TP matrix – thermoforming of a biodegradable multiaxial flax/PLA fabric

Electric household appliances

Source: *Domena*

According to a study by the household appliance manufacturers association GIFAM[1], 55% of French citizens consider that the environmental characteristics of an appliance are more important than its price, suggesting worthwhile prospects for these products.

One brand has already incorporated 30% natural hemp fibre into its steam iron stations, providing advantages like weight reduction, improved recycling and, especially, products that can be taken apart and repaired.

1 *Groupement Interprofessionnel des Fabricants d'Appareils Ménagers*

Source: *Plasticana*

Boots, jelly sandals, handbags

One French company specialising in bags and shoes made with recyclable materials has developed a plastic with vinyl matrix and 30% hemp fibre reinforcement, and which can be injection moulded, infusion moulded or calendered.

Besides having intrinsic properties that give a lightweight flexible product with torsional strength, hemp fibre can fix four times as much carbon during its growth than a wet tropical forest.

9. Street furniture

As environmental regulations become tighter and tighter, flax-fibre and hemp-fibre reinforced composites appear to be a replacement solution with many advantages.

The use of flax or hemp in composites has environmental and economic advantages that are becoming imperative:

- unlike glass fibre, flax and hemp fibres can be incinerated with a net zero carbon footprint and without leaving residues, and thus be upgraded into energy;
- compared to aluminium, processing these fibres consumes much less energy, thereby reducing cost.

As regards mechanical properties, flax and hemp fibres are:

- strong, and about as stiff as glass fibre;
- less likely than glass fibre to cause cuts if they break;
- lightweight, facilitating transport and handling.

Pedestrian signs

Source: *Ondelia*

In strips for pedestrian signs or plates for street signs, composite substrates for signs are made from a 55% bio-sourced plant resin reinforced with flax fibre.

The resulting substrates have bending stiffness equivalent to that of aluminium, and are entirely recyclable at end of life. They can also receive an anti-graffiti treatment.

A new company installed in the Normandy flax-growing region is making sign panels that are very popular with some of the municipalities, which have included them in their “Agenda 21” sustainable development programmes for the twenty-first century. This initiative featuring entirely local production of an entirely renewable resource is practically carbon neutral.

Bicycling signs

Source: *NPSP*

These signs for bicycle traffic are made using a closed vacuum-assisted (VA) RTM process with a polyester matrix reinforced with flax or hemp fibres.

Life cycle analysis has confirmed the environmental advantages of these sign panels, in particular with respect to the energy consumed during the production process: 40% lower than for standard signs. The signs also have high resistance to ultra-violet rays – indispensable for outdoor material – and M1-M2 fire resistance properties.

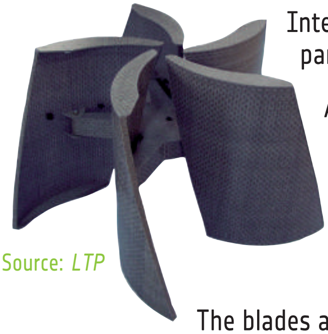
Street furniture

These pieces of street furniture – boxes for plants, waste paper/dust bins, portable cabins and fences – are made of extruded PVC (40%) with short hemp fibre (60%) reinforcement, resulting in highly stiff, heat-resistant products with optimum, durable CO_2 storage.

In France, both the Grenelle Environmental Forum and the "New Public and Private Buildings Committee" have already taken note of hemp, which the draft law for implementing the Grenelle includes as one of the top renewable biomaterials in terms of low energy consumption. So it is no surprise that municipalities are taking a lively interest in these fibres.

Source: *Agrochanvre*

10. Wind energy



Source: *LTP*

Integrating flax fibre into the wind turbine manufacturing process is part of a global eco-design process.

A prototype for wind turbine rotor blades was created using a 40% flax textile reinforcement commingled with a PLA matrix. The flax/PLA fabrics were compression moulded (hot compaction) to make extremely strong blades.

The blades are lightweight, thanks to the flax fibre's low density yet excellent stiffness properties, and the fibre's high breaking strain gives the blades significant mechanical strength (tensile, compression, torsion), crucial for operation during strong winds and to optimise energy production.

The vertical wind turbine is designed to supply energy-independent public lighting systems, and has the further advantage of being 100% bio sourced and biodegradable.

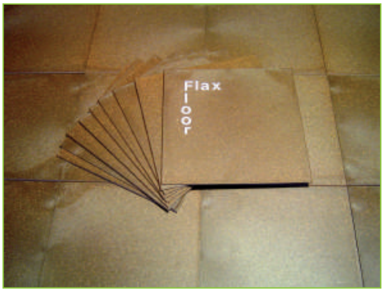
The vertical wind turbine won the 2010 JEC Award in the wind energy category.

11. Home improvement

Fans of environment-friendly habitats are always looking for lightweight, recyclable and hypoallergenic materials, so natural-fibre construction materials are very popular with them. There are more and more of these consumers, and they pay a lot of attention to the environmental properties of materials, as much to preserve nature as to clear their homes of the "pollution" of allergenic materials. The return to "local product" values constitutes yet another potential opportunity for composites reinforced with flax and hemp – fibres that are grown in Europe.

Indoor and outdoor floor tiles

Ventilation is a key factor in home construction. Flax and hemp absorb moisture from the air and release it to the exterior when the ambient humidity decreases. As a result, the fibres "breathe", thereby regulating the flow of water vapour that arises from the differences in indoor and outdoor temperatures.



Source: *Dehondt Groupe*

These natural fibres make for comfortable installation, with no risk of irritation for skin or eyes. They have a very low static charge and no electromagnetic current conductivity.

An injection process can be used to reinforce a PA11 thermoplastic resin with 30% flax fibres to create floor tiles that are offered in several different colours.

Bathroom fittings

A thin, watertight layer of flax fibre is used to reinforce waxed concrete for use in bathrooms

Source: *NPSP*

from the floor to ceiling, including counter-tops, wash basins, shower stalls and even curved bathtub surrounds.

In fact, poured fibre-reinforced concrete is a mixture of extra-fine constituent materials (including the fibres) that is self-consolidating. Its flowability enables the highly accurate reproduction of the polyester resin matrix, to which synthetic dyes or natural pigments are added to give it its hue.

Besides low density, the fibres have many other advantages:

- an agreeable feel to them;
- a hollow morphology and modulus of elasticity that give materials sound and vibration damping properties, and therefore good acoustic comfort;
- a natural humidity that allows producing composites with enough conductivity to let static charges flow;
- adaptability to heat cycles (vapour absorption).

Decking for terraces

Source: *Agrochanvre*

As functional materials, floor coverings must be leakproof, weather resistant, and attractive.

An extrusion process is used to make floor tiles in PVC reinforced 50% with hemp. The hemp-reinforced tiles have mechanical properties equivalent to those of PVC/glass tiles, as well as definite functional and aesthetic qualities. They provide a practical alternative to the use of the most expensive, highly prized exotic woods. Hemp-reinforced decking is equally suitable for outdoor community facilities and for comfortable fittings for private gardens.

The decking is rot proof and durable, comfortable to walk on with no risk of splinters, and non-skid, even when wet; the assembly system with invisible fixations is standard and cost-efficient.

Sections for windows

Thus far, the use of flax-reinforced window sections has been limited to home interiors. These sections are suitable for passive housing with very low energy consumption.

Source: *Innobat*

Besides its low environmental impact, the flax offers thermal benefits and high mechanical strength. The product design is based on flax prepreg rovings and a pultrusion process, with 65% flax reinforcement for a biosourced epoxy resin.
The flax section for window won the 2011 JEC Award in the biobased category.

Triple glazing is becoming increasingly standard in construction. This requires compensating for the extra weight, which flax is well suited to do, thanks to its low density.

Switches and cable trays

Manufacturers of interior electrical equipment (outlets, cable trays and switches) are currently experimenting to substitute flax-or hemp-reinforced plastic accessories for the non-degradable mineral fibres in some electrical equipment.
While the tests are concerned with aesthetic considerations, they also constitute an attempt to respond proactively to any tightening of REACH regulations that could restrict or even prohibit the use of certain PVCs in the short term.

12. Design

In the design sector, flax and hemp fibres are used mostly to create structural parts. Designers are very interested in their intrinsic properties, which include strength, low weight, flexibility, agreeable touch, lack of abrasiveness, UV resistance and biodegradability. These pioneering designers develop more or less limited series and do not hesitate to use flax and hemp composites to create complex shapes. The fibres usually show at the surface of the finished product, as the flax and hemp are an integral part of the aesthetic effects.

Coffee table, chair, armchair

Source: *Saint Luc/D.C.S*

- Thermoset-matrix composite with 70% multiaxial flax reinforcement (500g/m^2), and a biosourced, epoxy matrix of 100% plant origin.
- Thermoset-matrix composite with 70% multiaxial flax reinforcement (500g/m^2), and a polyester matrix.

Processing: RTM, injection moulding

Table

Thermoplastic-matrix composite with commingled flax/PLA fabric reinforcement and cork-core sandwich structure.

Source: *M DESIGN © Blinky*

Armchair

Source: Studio Aisslinger © Michel Bonvin

Thermocompression process to create a structure with 70% nonwoven hemp reinforcement and water-based acrylic matrix.
The one-piece armchair is perfectly stiff.

Source: NPSP

The flax is used in combination with a transparent bio resin, making the plant fibre visible.

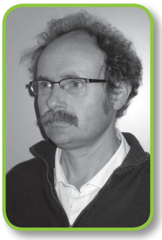
Indoor/outdoor lighting

Source: Az&mut

A drape-formed lamp with 70% multiaxial flax reinforcement and polyester matrix.

Due to their resistance to mildew and moisture, flax and hemp fibres can be used in lampshades for outdoor use.

- IX - Eco-design, Life Cycle Analysis (LCA) and Recycling



Christophe BALEY,
Professor at the University of Bretagne Sud, LIMAT[B], France

Antoine LE DUIGOU,
Assistant professor at the University of Bretagne Sud, LIMAT[B], France

LIMAT[B]: (laboratory of engineering of materials of Bretagne)

1. Introduction

Humans have used natural materials such as wood, plant fibres and silk for centuries. However, human activities have negative environmental impacts, such as:

- exhaustion of non-renewable natural resources,
- climate change,
- pollution of water, the atmosphere and the ground,
- waste production,
- reduced biodiversity,
- degradation of nature,
- noise.

Environmental concerns, the limited resources of the Earth, and the end of cheap petrol are creating opportunities for new markets for biomass materials. In this context, the use of plant fibres as reinforcement for plastics is being developed. But does this development really reduce environmental impacts? Even though the fibres have a natural origin, answering this question requires a global view. There is no point in promoting the introduction of natural fibres as composite reinforcements simply as a marketing exercise ("green-washing"), as this will result in a loss of confidence in the product. Today, eco-design is becoming more popular and it is important to discuss environmental impacts and the tools available to quantify them, such as life cycle analysis (LCA). This chapter will examine this subject, though it should be emphasised that in a limited space, only an introduction to this complex subject can be provided. A list of references is given at the end of the chapter to enable the interested reader to obtain more details.

First eco-systems will be presented, in order to introduce eco-design. Then the concept of life cycle will be introduced. LCA will then be described, and two case studies will be presented: a comparison between flax fibres and E-glass fibres, followed by a comparison between flax/PLLA and E-glass/polyester composites. Finally, the recycling of composite materials will be described.

2. Ecosystems

The environment is a complex entity involving physical media (water, air, ground), living creatures and natural resources. A system defines all the elements of this entity and the interactions between them.

In ecology, an ecosystem designates the unity formed by an association or community of living creatures (biocoenosis) and their geological, hydrological, and climatic environment (the biotope). The elements of an ecosystem develop a network of exchanges of energy and matter enabling life to exist and develop. Figure 1 shows a natural ecosystem with energy provided by the sun (an open system) and no waste. It is important to note that nothing is lost, nothing is created; everything is transformed.

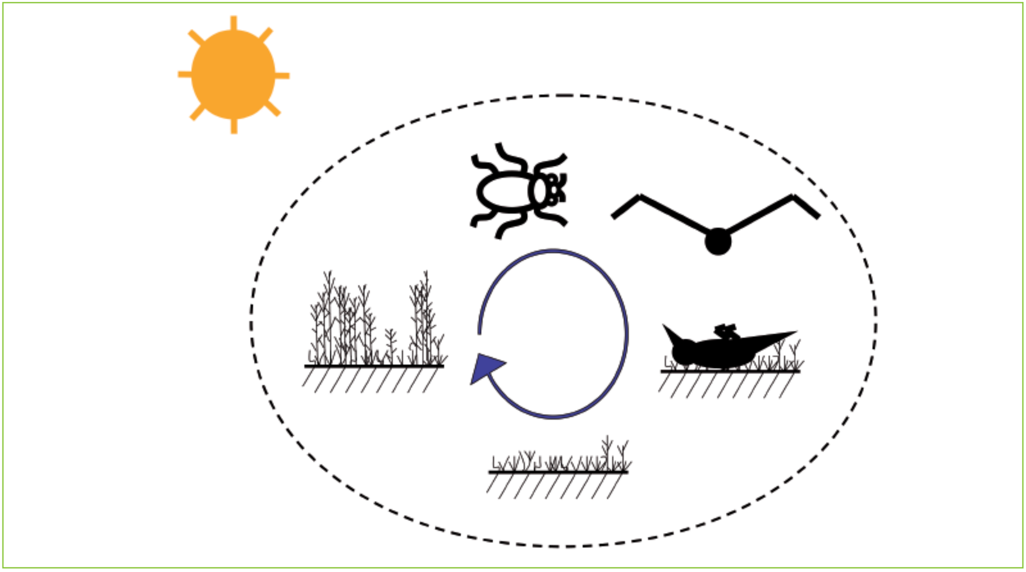


Figure 1: A natural ecosystem.

Our society is organised as if the world disposes of unlimited resources and the planet has an unlimited capacity to absorb waste (Figure 2). This must change, by choice or necessity, as the system is not sustainable.

Figure 2: Current societal model.

Awareness of this has resulted in changes such as the European directive to achieve a 20% reduction in greenhouse gases by 2020, to increase the share of renewable energy, and to improve energy efficiency. In this context, carbon in plants – and more generally the increased use of biomass (matter, energy) – is particularly attractive.
We use composite materials today to produce lightweight, high-performance components such as aircraft structures. This reduces weight and hence fuel consumption during flight. There is a logic of optimisation towards "the inevitable renaissance" of minimum energy structures. The use of natural fibres as a composite reinforcement follows that logic, as they require less energy to produce and are biodegradable (natural decomposition after use).

3. Eco-design

Eco-design can be described as an innovation method that integrates the environment into the design of products in order to reduce environmental impact. The word "product" is used here as a general term including objects and services. Rather than healing, eco-design aims at prevention, with an approach based on continuous improvement. Schematically, to satisfy the usual criteria used in design (customer needs, technical feasibility, cost reduction), the solution retained is to be found where the three areas overlap. The addition of a fourth area (environment) further restricts the solutions available to where all four areas overlap.

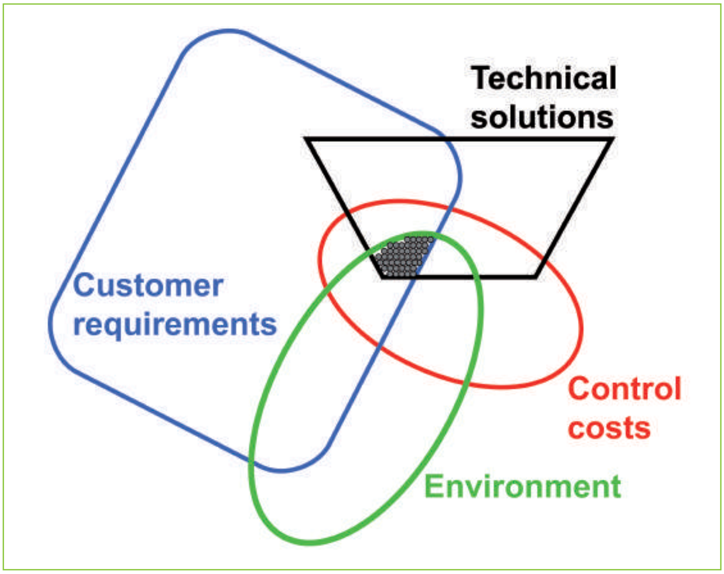


Figure 3: Schematic representation of eco-design.

Eco-design enables the environmental management to be centred on the product. This approach has been standardized in XP ISO/TR 14062 (January 2003) [1]. The standard is entitled "Environmental management - Integration of environmental aspects in the design and development of a product".

4. Life cycle analysis

a) Definition & aims

Life cycle analysis (LCA) is a global, multi-criteria tool for eco-design (Figure 4) that enables the environmental impacts of a product or system to be quantified. It is a global approach, because the complete life cycle of the product or system can be included from cradle to grave. Unlike the carbon footprint, which is only based on one indicator (climate change), the LCA includes a selection of multi-scale criteria. The application of this tool has been standardised in ISO 14040 [2] and ISO 14044 [3].

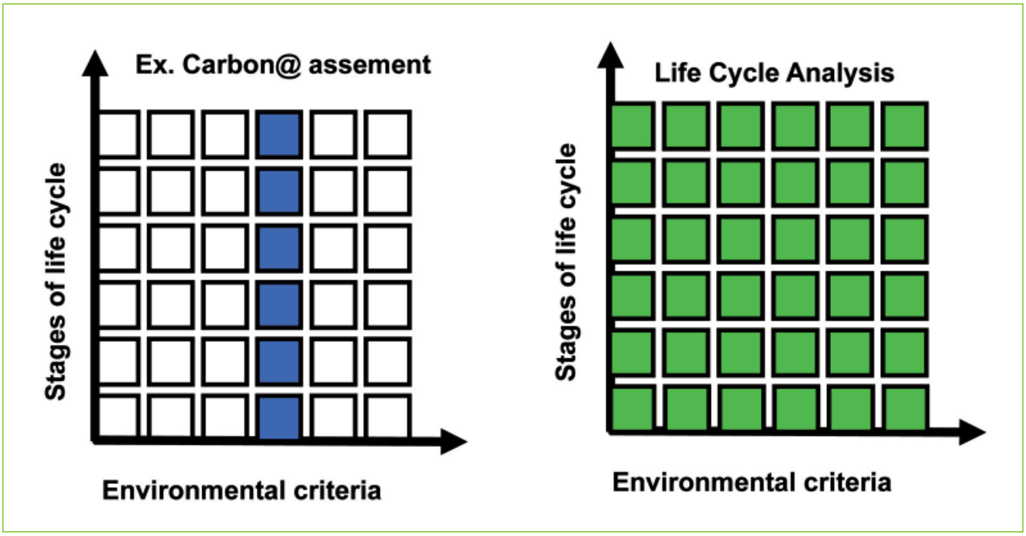


Figure 4: Global and multi-criteria view of LCA.

The main objective of an environmental analysis is to reveal environmental weaknesses. The global multi-criteria approach allows transfer of pollution between steps or indicators to be predicted, as shown in Figure 5.

LCA also provides assistance in decision making, both externally (in defining public policy, developing procedures, etc.) or for internal use (investment, new technology, etc.). It allows the environmental aspects that define the ecodesign approach to be evaluated. However, it is not easily adaptable to all situations and has its limits. It is a technique that provides some elements but requires interpretation, and should be based on the input of all the parties involved.

b) Description of the method

The LCA methodology is described in detail in the ISO 14044 standard [3]. Figure 6 summarises the procedure to follow in performing an LCA.
The LCA starts with the definition of the objectives and the limits of the study, i.e. a clear and precise description of the problem. This step is essential, as it enables subjective interpretations to be avoided. The objective is described in terms of the applications envisaged, the reasons for performing the analysis, and for whom the analysis is intended. The area of study includes the limits of the system (time, place, technologies and impacts).

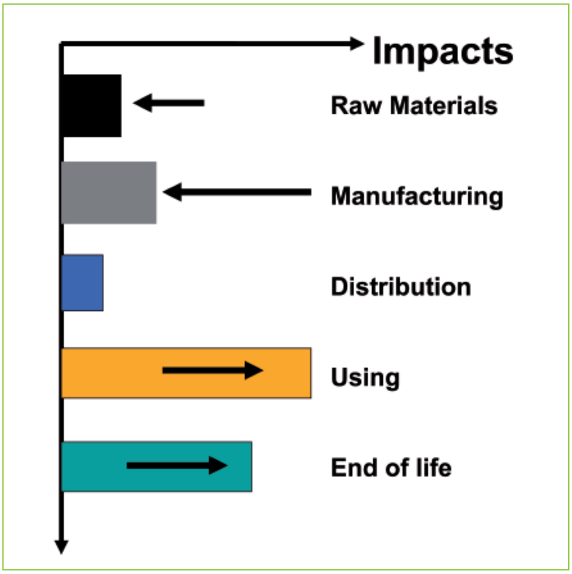


Figure 5: Principle of pollution transfer.

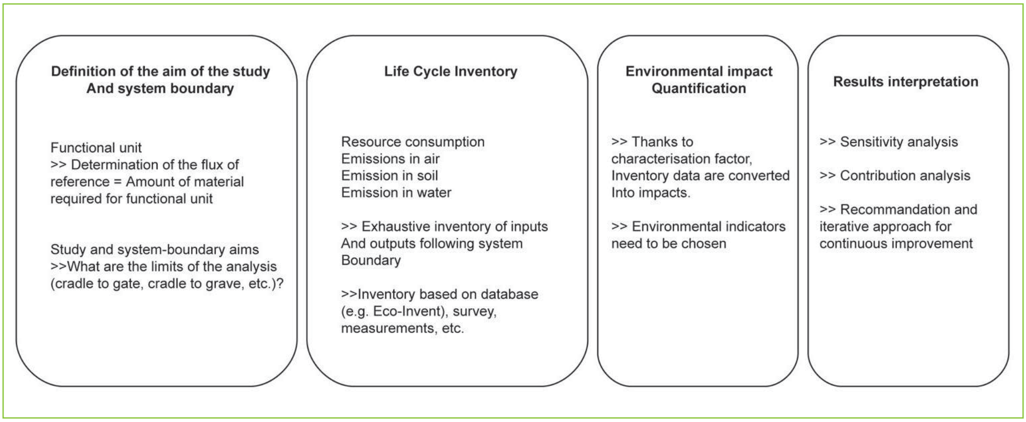


Figure 6: Details of the different steps in a life cycle analysis.

The LCA must be performed with respect to a function, a need, or a service. It is necessary to define a quantifiable functional unit for the product or service as defined by the ISO 14040 standard[2]. This is defined as the quantified performance of a system of products destined to be used as the reference unit in a LCA. In other words, it is necessary to reason in terms of an equivalent delivered service.

Once the basics of the study have been defined, corresponding to the objectives defined previously and the functional unit, the life cycle inventory is made. In practice, this involves making as detailed a list as possible of all the fluxes of natural resource consumption (minerals, water, etc.), of energy (oil, gas, carbon, wind, etc.) and environmental emissions for each of the steps of the system under study. This necessarily requires the use of LCA software and databases. A lack of reliable information in the databases constitutes a critical point during the

inventory, before the often long and difficult investigation process begins, involving bibliographic searches and/or the setting up of measurement campaigns.
The data collected are organised within scenarios, which mirror the life cycle and can be predictive or exploratory. New scenarios can be imagined, e.g. the industrial composting of biocomposites from automobiles.

These fluxes are then transformed into environmental impacts: this is the life cycle impact assessment or environmental balance sheet. According to the ISO 14001 standard[4], an environmental impact is any modification to the environment, negative or beneficial, resulting totally or partially from the specific activities, products or services. Among the best known are:

- the climate changes related to the increase in atmospheric concentration of greenhouse gases such as CO_2, CH_4 or N_2O;

- eutrophication, which indicates a lack of equilibrium in the aquatic medium resulting from excessive nutrients (nitrogen, phosphorous, nitrates) that increases the production of algae;

- photochemical oxidation, corresponding to the creation of ozone in the lowest layer of the atmosphere by the degradation of nitrogen oxides and hydrocarbons (from industrial solvents and unburned exhaust gases from vehicles) through the action of the sun's rays;

- The hole in the ozone layer caused by the action of fluoride and chloride components (CFC, HCFC) and nitrogen oxides (exhaust gases) in the degradation of the protective ozone layer in the upper atmosphere.

The ISO 14044 standard[3] provides a framework but does not specify which environmental impact indicators should be evaluated. The standard simply states that they should be relevant and robust (i.e. not open to criticism). For the LCA of a flax shirt compared to a cotton shirt[5], for example, 12 indicators were studied to evaluate potential environmental impacts. The indicators must be chosen to allow the communication of relevant results. Thus it is necessary to consider the intended audience and the appropriate rules applying to the industrial sector concerned (packaging, automobile, aeronautical, etc.).
The life cycle inventory is transformed into environmental impact indicators through the use of characterisation factors that express the contribution of each of the substances in the inventory with respect to a reference substance (e.g. the equivalent CO_2 for climate change). The substances chosen as reference units and the characterisation factors must have a wide consensus among the experts of the scientific community concerned by each impact. Figure 7 shows with a simple example how the environmental impacts are calculated for a polypropylene component according to ISO 14044 standards.
A standardisation step can be added, e.g. with respect to the average effect caused per year by one European inhabitant. By doing so, the relative importance of the different environmental impacts can be compared.

The final step in the LCA consists of the analysis and interpretation of the results in relation to the functional unit. The aim is to examine the relative importance of the results of the environmental evaluation, impact by impact. There is sometimes a desire to produce a single global indicator (unique score) to make interpretation easier, but this is open to discussion. The unique score yields less "exact" results and is based on a subjective perception, while the ISO 14040 standard [2] stipulates that if such a weighting is used, the untreated results must also be provided.

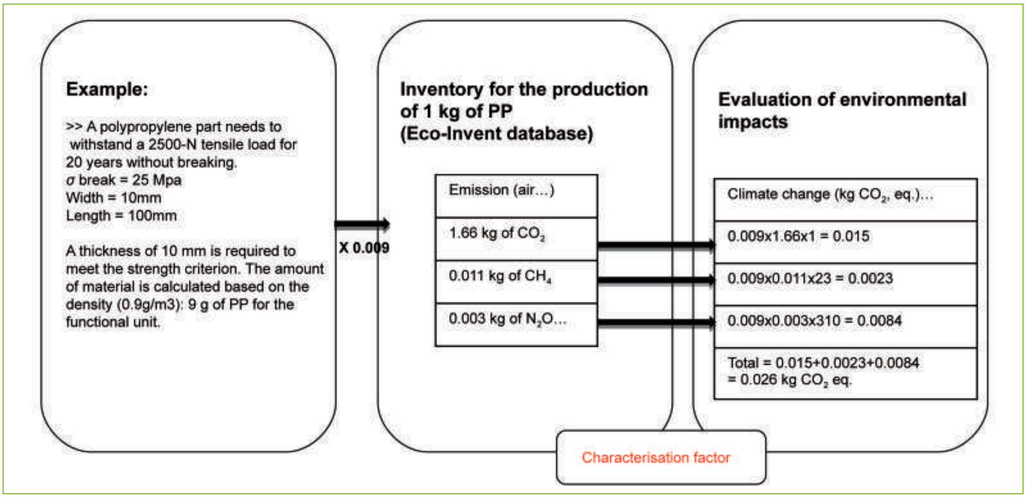


Figure 7: Example of climate change impact calculation for a polypropylene component for a given functional unit.

During the analysis and interpretation phase, the coherence, exhaustiveness and sensitivity of the results must be verified. The aim of the sensitivity analysis is to determine whether the initial assumptions, methods and data used are in agreement with the objectives and the limits of the study. This requires the stability of the system to be validated, and the influence of uncertainties on the data and calculation methods to be checked. The main contributors (substances, process and life cycle) to the LCA must be clearly identified, together with the limitations and recommendations.
If there is to be public diffusion of the results, a critical review by a panel of independent experts is obligatory. The aim of such a review is to verify the hypotheses, validate the results, verify the objectiveness of the study and that the ISO 14040 and 14044 standards have been followed [2, 3].

c) Limitations

The scientific limits of this approach are due to the fact that the LCA cannot model all the criteria. In addition to the environmental evaluation, other criteria such as the social and economic dimensions must therefore be taken into consideration. There may also be difficulties in obtaining all the fluxes. For these reasons, various industrial sectors have put together working groups in order to generate reference data.
With respect to calculating the indicators, neither the synergies or other interactions between pollutants, nor the characteristics of the receiving medium are explained. Some evaluation methods are of questionable scientific validity (e.g. an eco-indicator with a unique score). Also, some information may not be reliable, or some phenomena may still be under evaluation (e.g. the toxicity of certain products). From a methodology viewpoint, the LCA may not be impartial if the initial assumptions are not independently evaluated. It is also difficult to compare two LCAs if the hypotheses and context are not similar. The risk of inverse LCAs, where the analysis starts from the results desired, may also be noted.
Other limitations are that most data are average data for a large area (e.g. Europe) and not specific to a single region or activity. Another one is the use of linear models for estimating the impacts, but we all know some impacts will be very low until a certain saturation level is

reached, after which their significance can suddenly soar.
Finally, one of the main limitations of LCA does not concern the analysis itself but the communication methods used to present the results. It is not easy to present scientific data simply and efficiently without ecological "greenwashing". This is one of the current challenges in this area. However, it should be mentioned here that LCA is the best we have at this moment to get a view on environmental impacts, and that large databases already exist.

d) Case study 1: LCA of flax fibres

Extensive work on natural fibres is already available in the literature. However, the simple fact that these come from renewable resources does not necessarily mean that their environmental impact is lower than that of traditional reinforcements. The aim of this section is to quantify the environmental impacts of flax fibres compared to glass fibres as a composite reinforcement. The results shown in this section come from the authors' work [6].

- Functional unit and system boundary

The functional unit in the present case cannot be simply based on fibres with identical mechanical properties. In order to simplify the comparison, the same weight of fibres (1 kg) will be compared. The study perimeter includes the culture, mechanical treatment (stripping and combing, in typical flax terms also called scutching and hackling) and transport between sites (Figure 8). Spinning, often used in the textile industry, is not used because it introduces twist and waviness in flax fibres, which results in a loss of mechanical properties of the composite, and hence is not wanted [7]. It also consumes a large amount of non-renewable energy.[8]

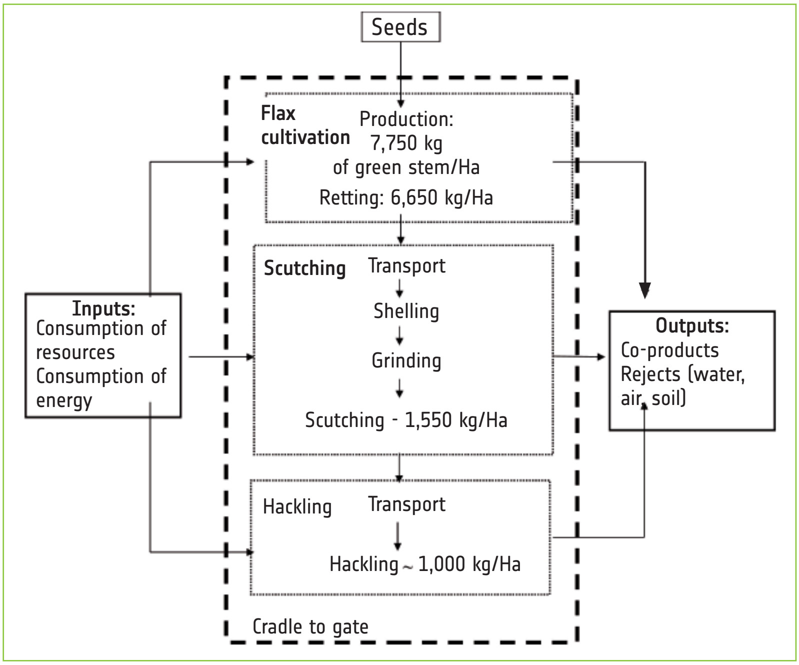


Figure 8: Diagram of flax fibre production, from the plant to the co-products, with yields (kg/ha). Cradle to product approach [6].




The production yields of fibres and co-products, taken from the work of Labouze et al. [5] based on the data of the Institut Technique du Lin (ITL), are introduced into the life cycle inventory. The cultivation of one hectare of flax plants produces 7,750 kg green stems, which become 6,650 kg of retted stems. The scutching step produces about 1,550 kg of stripped fibres (dm)*, 850 kg of tows (dm-cm*), 365 kg of seeds, 2,960 kg of shives, 530 kg of flakes, and finally 665 kg of powder. Combing (or hackling) the stripped fibres yields around 1000 kg of hackled (dm) fibres, 465 kg of tows (dm-cm) and 85 kg of powder.

A first question when running an LCA is whether these products are waste or co-products. A recent European Union directive [9] proposes distinguishing waste products from co-products when the following four conditions are satisfied:

(1)There is a definite use for the substance or object.
(2)The substance or object is an integral part of the production process.
(3)The substance or object can be used directly without another production step, other than that of a common industrial practice.
(4)The substance or object does not produce any product harmful for human health.

In addition to the long fibres, the other products are commonly used in diverse applications. For example, one hectare of flax can produce, apart from the textile, 1000 car-door panels made from flax tows (dm-cm) used as non-woven, 300 m² of straw, 200 kg of animal feed, and 100 litres of oil [10]. Condition (1) is therefore satisfied. As combing of fibres occurs at the end of the production process, the production of tows, flakes and shives is unavoidable. This satisfies condition (2).

The shives can be used directly in agricultural straw, or as animal feed. The tows require a thermal compression operation to be transformed into door panels. The additional steps are thus limited and in accordance with condition (3). Contrary to glass fibres, natural fibres are not considered to be irritants, so condition (4) is satisfied. It therefore appears essential to include the added value of co-products in an environmental evaluation of flax fibres.

There are different ways of integrating the co-products in the calculation of the environmental impacts, according to the weight, economic or energy contribution of each (Figure 9). Depending on this hypothesis, results can change. For example, from the weight allocation viewpoint, hackled flax fibre represents around 15% of the retted flax, while from the economic allocation viewpoint, these fibres represent around 80% of the price of the product.

The allocation method is open to discussion, since the fibres are the main economic reason for producing these plants, although the fibre weight is quite small [8]. One disadvantage of an economic value allocation is price fluctuations. For example, Turunen et al. [8] showed that a decrease in the price of long fibres with respect to short fibres could reduce eutrophication by 24% and land use by 28%. However, the Society of Environmental Toxicology and Chemistry SETAC strongly recommends applying an allocation procedure based on physico-chemical considerations. Thus, a weight-based allocation, even though it does not strictly reflect the main objectives of the flax growers, does correspond to the physical yield of flax cultivation [11].

Even though weight allocation is regularly used for studies in which the functional unit is related to the weight of a product such as natural fibres [12], it appears wise to run both methods in order to get a better view of the points that could be improved.

**Refer to Chapter 10*

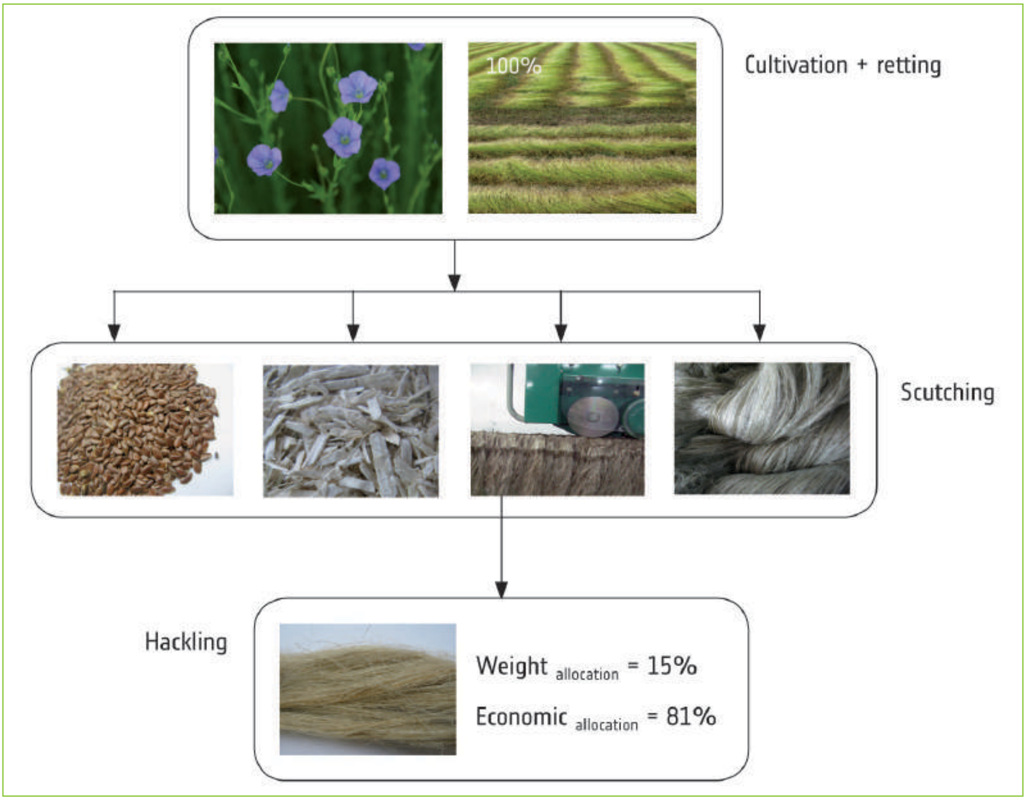


Figure 9: Diagram of allocation methodology = Impact share.

- Environmental assessment of flax fibres compared to glass fibres

Figure 10 presents the environmental indicators for the production of one kg of combed or hackled flax fibres compared to one kg of glass fibres.

Compared to glass fibres, the production of hackled flax fibres results in a significantly reduced environmental impact, with 90% less depletion of abiotic resources, 98% less human toxicity, and 88% less photochemical oxidation. It can be noted on Figure 11 that the global warming indicator is negative for flax production. This is the result of taking account of CO_2 sequestration by photosynthesis [13].

Contribution analysis shows that the production and use of ammonium nitrate are the most negative contributors to the global warming indicator. Taking account of photosynthesis is globally positive for the climate and a major advantage of the use of biomass rather than fossil resources. The impact of hackled flax fibre production on acidification is around 80% lower than that of glass fibre manufacture. Once again, the use of fertilizers – ammonium nitrate and in particular, triple superphosphate – contributes the most (around 49%) to the overall impact.

There is also a non-negligible contribution from the electricity required for scutching and hackling (17%). Land use (around seven months per year for production of flax) appears to be very negative for flax fibre production compared to glass. However, one needs to consider how important the land use in the LCA is compared to other impacts. Land use is indeed an inherent aspect of agricultural production and does not take into account the inevitable rotation of cultivation. Moreover, flax cultivation is known for being a very good break crop compared to canola and wheat.

Globally, the production of flax fibres appears to be an environmentally attractive alternative to glass fibres. However, further analyses should integrate the complete life cycle for biocomposites, as examined in the second case study below.

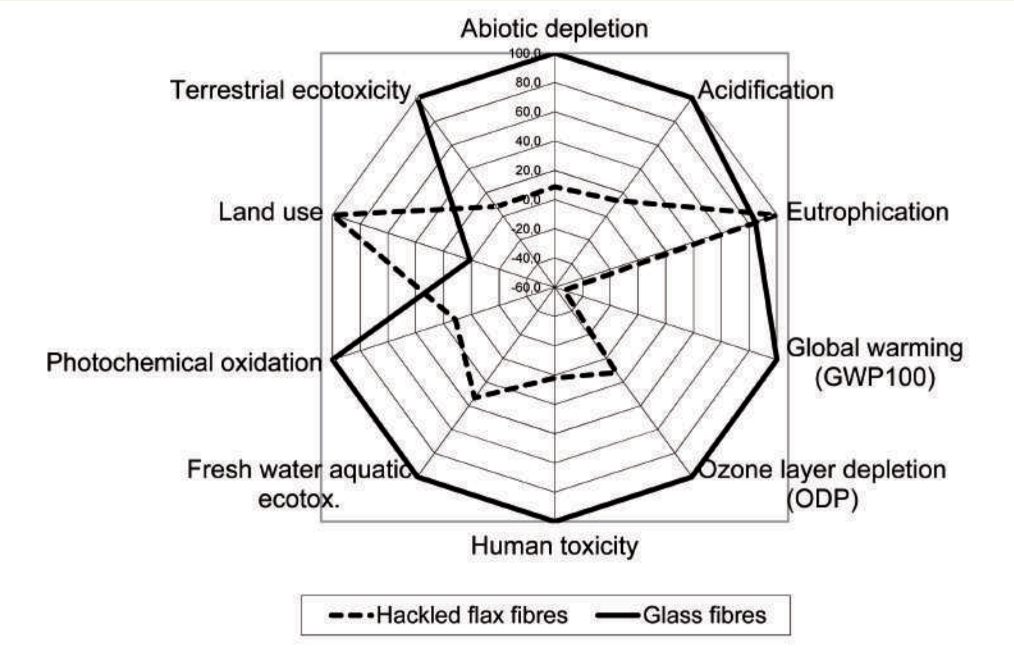


Figure 10: Environmental impacts during the production of combed flax fibres compared to those for glass fibres [6].

e) Case study 2: Life cycle analysis of Flax/PLLA biocomposites compared to glass/polyester composites LCA and flax fibres

Here, we compare the environmental impacts of two composites (glass/polyester composites and flax/PLLA biocomposites). The results are again taken from the authors' recent studies, and more details can be found in reference 14.
We take incineration and landfilling into account, on the assumption that biocomposites can be managed in the same way as glass/polyester composites. Figure 11 shows the environmental results for biocomposites compared to glass/unsaturated polyester.

The biocomposites show seven favourable indicators out of 10, compared to the glass/polyester (Figure 11), including climate change, abiotic resource depletion, and ozone layer depletion. With respect to the production phase, the eutrophication, marine ecotoxicity and land-use impact indicators are higher for the biocomposites.
Incineration is more favourable for biocomposites than composites, due to flax fibres, which supply energy (19.46 MJ/kg [5]). Glass fibres are considered to be non-combustible, and require an input of energy during incineration (1.7 MJ/kg [15]). All the results indicate that biocomposites consume less non-renewable energy than glass/polyester composites.

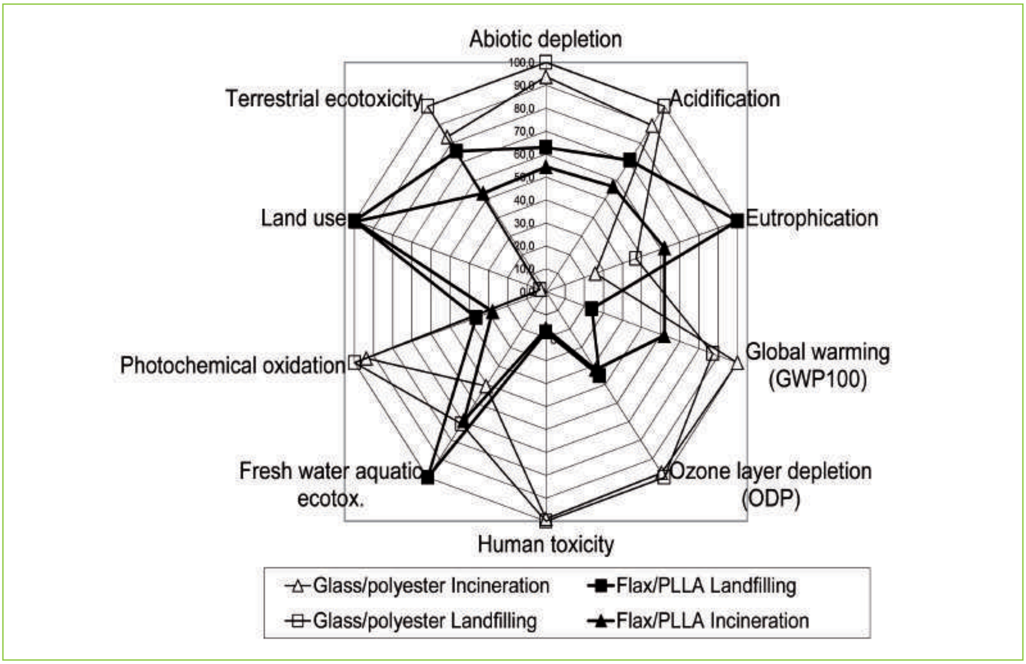


Figure 11: Comparison of environmental impacts for Flax/ PLLA biocomposite and glass/Polyester composite. Incineration and landfilling [14].

The end-of-life scenario influences the biocomposite impacts. For example, landfilling increases their global life cycle impact (e.g. 60% more eutrophication, 77% more marine ecotoxicity) compared with the values obtained during their production. This can be explained by the leaching process during burial. The contribution to climate change impact during landfilling is small, however, due to biogenic carbon storage. Landfilling has a small influence on non-renewable energy consumption of biocomposites compared to the production phase.
The incineration of biocomposites contributes positively to five out of 10 impacts due to energy recovery, which reduces electricity production (e.g. 20% less acidification, 26% less terrestrial ecotoxicity, 21% photochemical oxidation). However, the climatic change impact is doubled, due to the release of temporarily stored biogenic carbon.

5. Recycling




Recycling is a treatment of waste (industrial or domestic) to allow the reintroduction of materials into the production cycle. This can be applied to both waste produced during manufacture and products at the end of their service life. Recycling has two major consequences for the environment:

- the reduction of the volume of waste, and thus of the pollution it causes,
- the preservation of resources, since recycled material replaces the new materials that would have had to be produced.

Figure 12 illustrates the benefits of recycling, with a comparison between the environmental impacts of new and recycled polypropylene (PP). The impacts of recycled PP are significantly reduced.

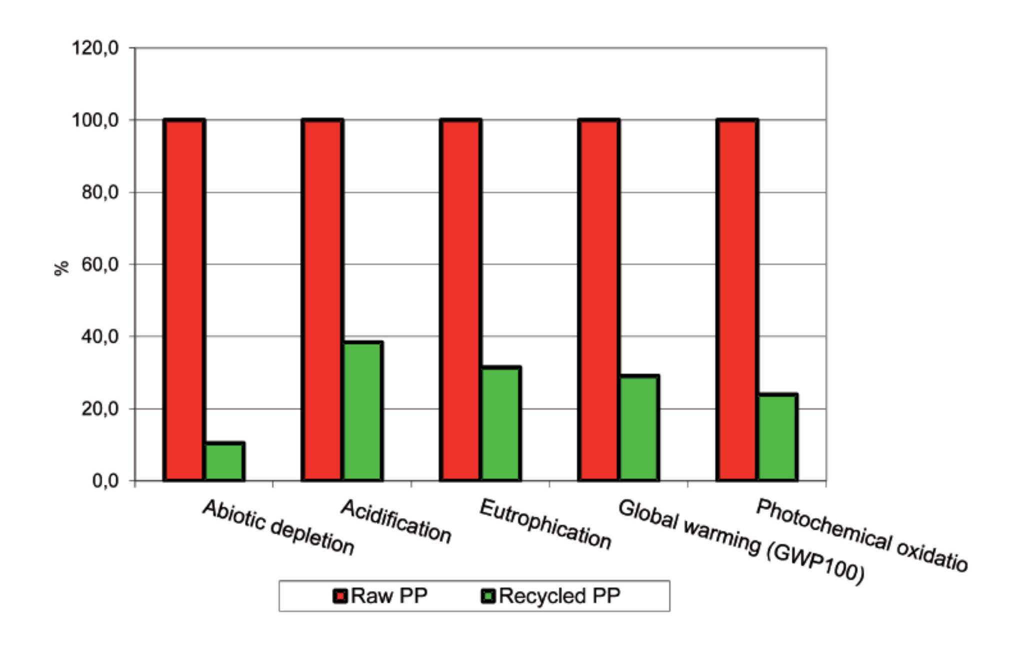


Figure 12: Environmental analysis of recycled PP against new PP production [16].

Recycling of materials is not a new idea – the practice of making new products from old has existed for many years, e.g. re-melting metal objects or recycling old paper to make new. It should be emphasised that before recycling, it is important to design products so that the majority of their constituents can be recycled (or re-used), and that it is equally important to reduce waste during production and to re-use products.

Some recycling processes are simple and cheap, others are complex, costly and polluting. Various criteria must be assessed in order to evaluate the potential for recycling and a detailed analysis of impacts must be made using LCA. It is important to examine things like organisation, the amount of energy to be recovered, or the relevance (based on LCA criteria) of recycling with respect to the raw material and the economics of the process.

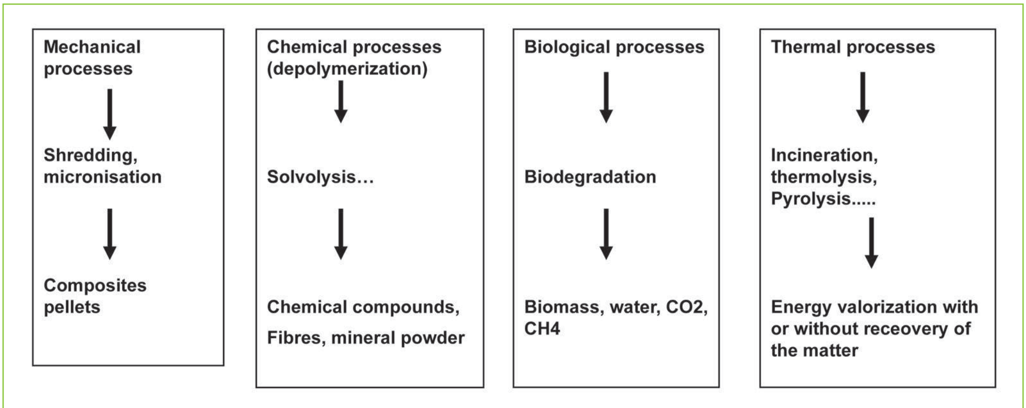


Figure 13: Recycling and recovery of organic matrix composite materials.

Different recycling strategies are possible, even if some are still only at the laboratory or prototype stage. These can be classified in four categories (Figure 13).

Mechanical processes

The component is ground and the material is transformed into shavings (including fibres and matrix). In general, this requires two steps: a rough grind at low speed to reduce the size of the waste, followed by fine grinding (with a hammer grinder) to produce fine micronised particles. For a thermoplastic matrix, the chemical structure of the polymer does not change during grinding and the shavings can be used in an appropriate transformation process (heating to melt the matrix and forming by compression moulding or extrusion/injection moulding). During the grinding operation, the fibre length is significantly reduced, but there are many composite components that are reinforced by short fibres and produced by injection. Recent work [17, 18] has shown that this approach can be used for composites reinforced with flax or hemp (with a PP or PLA matrix for example); during grinding and forming, the fibre bundles are cut but they also split into finer fibres (Figure 14), so the fibre aspect ratio is not greatly affected and the mechanical performance (stiffness and strength) is maintained.

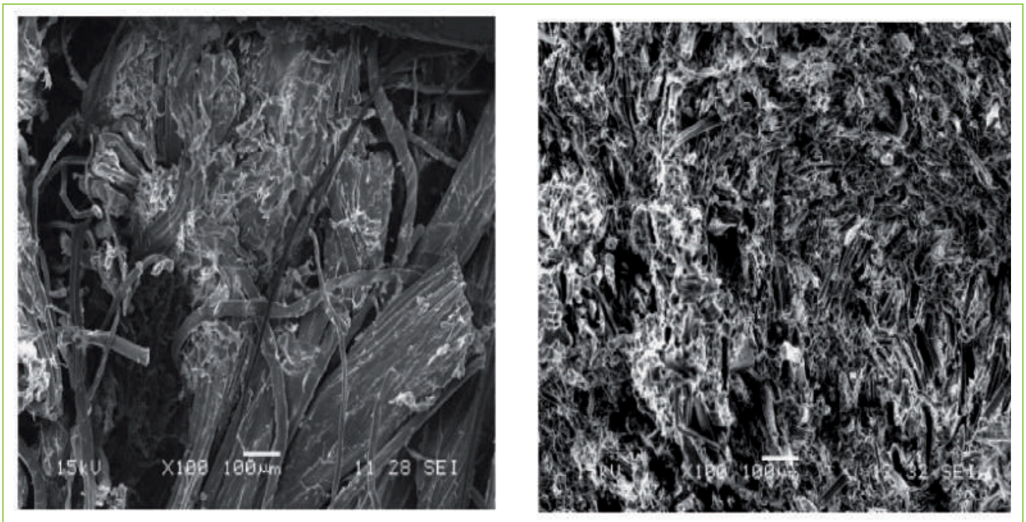


Figure 14: SEM micrograph of the fracture surface of BC-20% after one injection (A) and 6 injections (B) [17].

Thermal processes

The calorific potential of waste is used to obtain thermal energy (energy recovery) and, in some cases, the residues can also be used for new applications (energy and material recovery). In a traditional composite reinforced by glass fibres, only the fibres remain after burning of the polymer. Natural fibres (as well as carbon fibres) will also burn, enhancing the energy recovery.

Chemical processes

The molecular structures of polymers, fillers and fibres are separated chemically. These can then be recovered and re-synthesised. This process is applied mainly to thermosetting matrix polymers (e.g. epoxies) which, due to cross-linking, do not melt, but degrade at high temperature.

Biological procedures
In this case, the material is placed in conditions that favour composting, and is degraded by living micro-organisms (e.g. fungi, bacteria or algae). Flax and hemp fibres are materials that have been manufactured and recycled naturally by biodegradation and new growth for centuries. Fibres from plants, naturally biodegradable, can be impregnated with a biocompostable matrix (PLA or PHA for example). At the end of its service life, a biocomposite component can be ground and placed in industrial compost. It should be noted that there are standards which define the biodegradability of a material. For example, the NF EN 13432:2000 standard [19] defines the requirements for the composting and biodegradation of packaging plastics.

By definition, a plastic is considered to be degradable if degradation results from the activity of micro-organisms naturally present in the medium. When the process occurs in the presence of oxygen, the residual products of this biodegradation are carbon dioxide, water, inorganic compounds and biomass.
In addition, a plastic is considered to be compostable if it undergoes a degradation by a biological process during composting, thereby producing carbon dioxide, water, inorganic compounds and biomass at a rate comparable to that of other known compostable materials (cellulose for example), without generating any visible or recognisable toxic residues.

Methane, generated during composting when oxygen is not present, is a potential source of pollution (greenhouse gas). However, this is usually recovered to be transformed into biogas, which can allow significant energy savings.

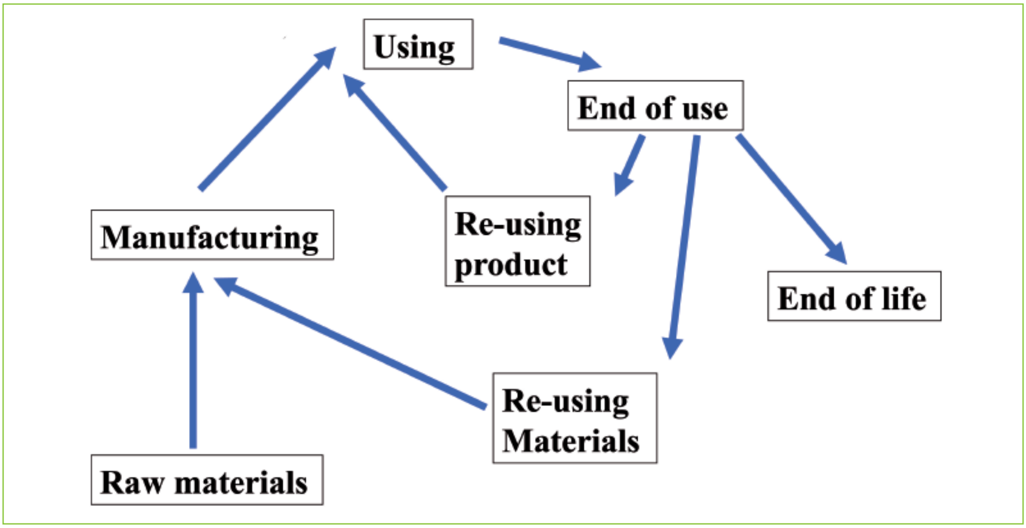


Figure 15: Simplified diagram showing different operations .

To validate any recycling operation, an LCA must be performed. A specific feature of the LCA is that the analysis can include the cycle from manufacture to end of life. With respect to recycling, the end of life poses a problem in defining the limits, as the matter, energy or biomass generated at the end of cycle N will provide resources for cycle N+1. It is therefore necessary to use a cradle-to-cradle analysis.

6. Conclusion

The importance of environmental issues is increasing both on a local scale (eutrophication) and a global scale (e.g. climate change). Certain directives have been put in place, in order to encourage more reasonable production procedures in which respect for the environment is taken into account. Ecodesign is an approach combining innovation and design that aims to reduce environmental impacts. This requires analysis tools. Life cycle analysis (LCA) is used to evaluate the environmental impacts (climate change, ozone layer changes, acidification, etc.) of a product or system throughout its life cycle, through standardised procedures.

Composite materials are widely used in industrial applications (aeronautical, automobile, pleasure boats, transportation), but their environmental performance is poor as they come from non-renewable (petrochemical) resources and their end of life is hard to manage and costly.

Certain natural fibres can be used as reinforcement in composites for which good mechanical properties are required. These fibres offer other specific advantages such as renewable cultivation, CO_2 storage, low energy consumption during production, durability, biodegradability, and incineration potential. While these materials should be examined on a case by case basis (it is difficult to generalise), the LCA examples shown in this chapter indicate that reductions in environmental impacts can also be achieved.

These materials also have an advantage in that they are recyclable in different ways:

- recycling the material by grinding the biocomposites and re-inserting them in the production cycle (extrusion/injection),
- biocomposting the biocomposites (with a biocompostable matrix), where these can be biodegraded under industrial conditions to produce water, CO_2, (or CH_4 under certain conditions) and biomass,
- thermal recycling to recover a quantity of energy equivalent to their calorific power.

In all cases, using natural fibre reinforcements and biocomposites provides interesting prospects for the development of environment-friendly materials. These prospects can be quantified through LCA, which requires a rigorous approach and a specific methodology (allocation, photosynthesis, etc.).

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- X - Availability and accessibility of flax and hemp for use as materials

1. Flax and hemp: the leading plant fibres in Europe

Producing 214,000 tonnes of plant fibres each year, Europe is the world's second-largest production basin for the fibres. It produces mainly flax and hemp, with an average annual 114,000 hectares under cultivation (2001-2008).

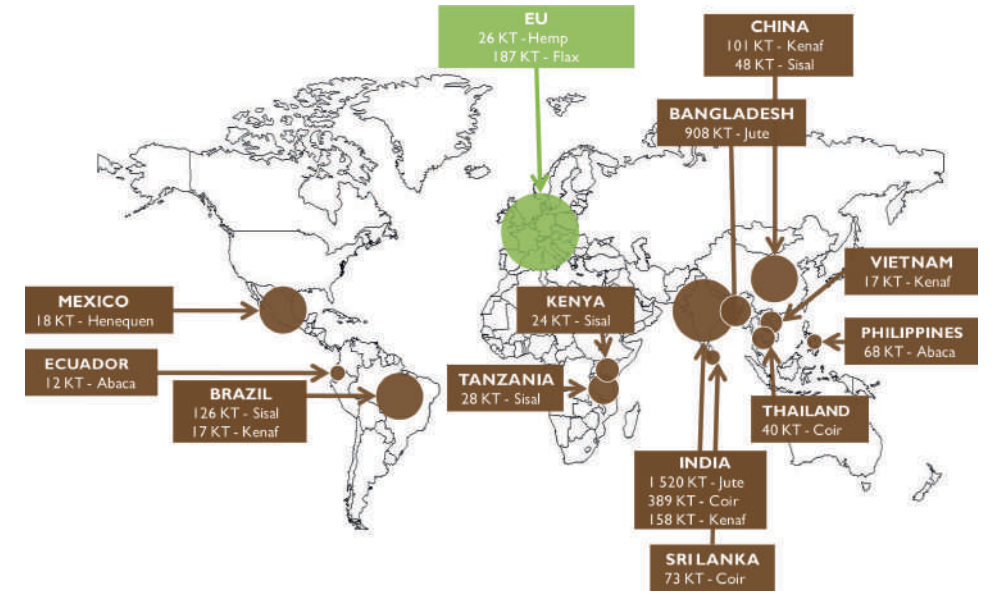

Figure 1: Distribution of worldwide plant fibre production, excluding cotton and wood (2001-2008). ***Source: F.R.D[1] for the ADEME[2]***

In terms of area planted in fibre plants, France is Europe's leading producer, with 82,000 hectares (or 72% of the European total). Belgium comes next with 16,000 ha (14%), then the Netherlands with 5,000 ha (4%). These figures are based on the averages for the 2001-2008 period.

France accounts for 75% of the roughly 100,000 ha of European area (2001-2008) planted in fibre flax, followed by Belgium with 16,000 ha and the Netherlands with 4,000 ha. It also accounts for 56% of the roughly 14,000 ha of European area (2001-2008) planted in hemp, followed by the United Kingdom and Germany, each with 1,700 ha.

In terms of weight, France is also the leading European producer, with 169,000 tonnes (MT) of plant fibre (80% of total European production, which is about 214,000 MT). Again, Belgium comes next with 25,000 tonnes, followed by the Netherlands with 7,500 tonnes.

1 Fibres Recherche Développement®, France
2 Agence de l'Environnement et de la Maîtrise de l'Energie, France / French Environment and Energy Management Agency

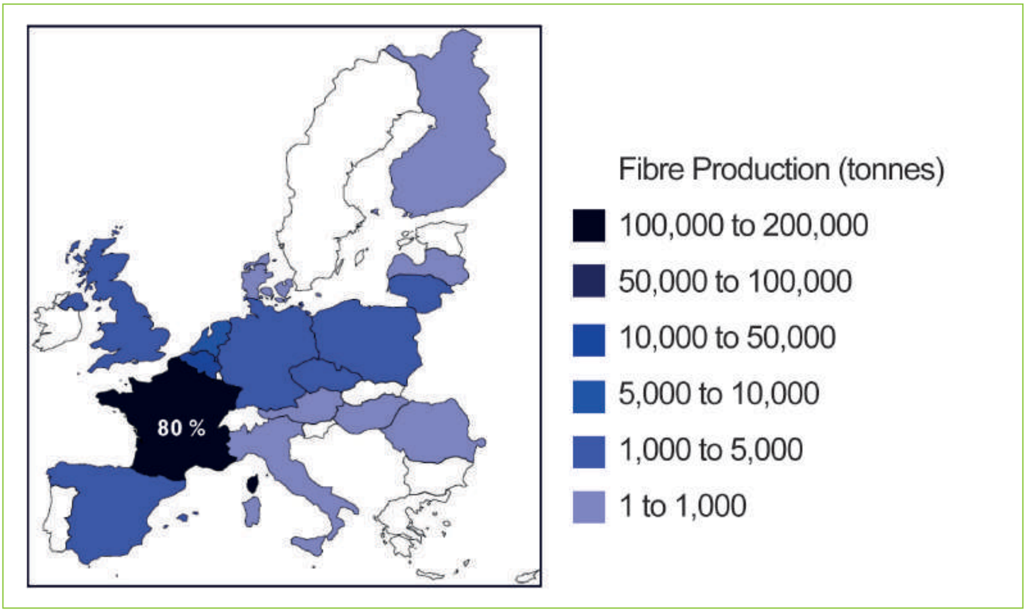

Figure 2: ***Source: F.R.D for the ADEME***

2. A well-organised industry

The agro-industrial flax and hemp value chains consist of four distinct segments, from upstream to downstream:

- production of the fibre plants that supply the straw;
- the first converting process, called "scutching";
- the second and third converting processes, where the products from the fibre extraction process are formed into semi-finished and finished products;
- the industrial application sectors that use these semi-finished and finished plant-fibre-based products.

The European flax and hemp Confederation-CELC (Confédération Européenne du Lin et du Chanvre) was created in 1951 to represent flax producers across Europe. CELC is the only European agro-industrial organisation that covers all stages of production and processing for flax and hemp. To provide support for the industry's players, a CELC Technical Uses Section was created in 2005, tasked with:

- organising initiatives relating to agriculture, industry, energy, research and the environment;
- coordinating activities around the development of recyclable resources and materials;
- setting up an exchange network with a continuously updated project database;
- conducting ongoing intelligence on programmes and initiatives in the markets concerned;
- working towards a sustainable development strategy for the industry.

3. Maturity of the European flax/hemp industry

The European flax and hemp fibre sector organises its capacities – from straw production to processing and distribution of these resources – within a dedicated industry that includes the entire value chain. Europe has invested high-level research and expertise to ensure that flax and hemp are easily available, fully developed fibres. Benefitting from industrial-scale production facilities, these are produced in large quantities and have recognised potential for material upgrade.

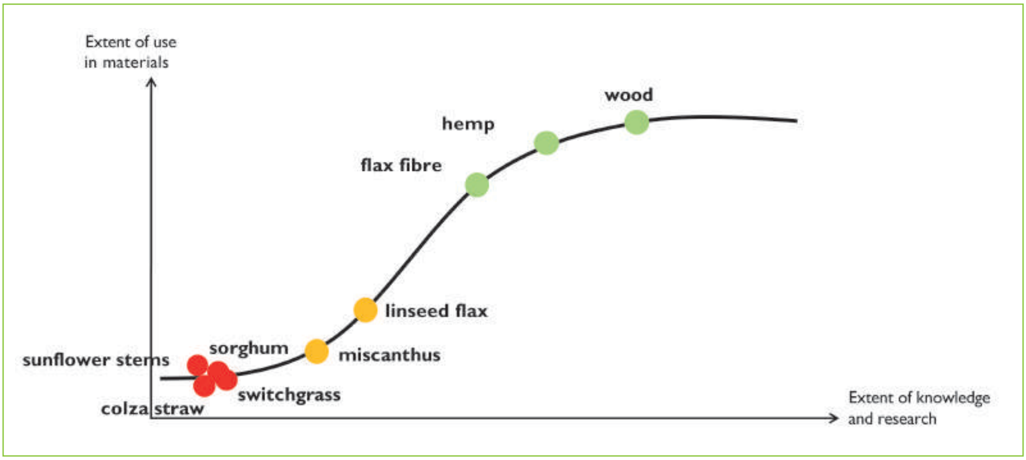

Figure 3: Plant fibres in France – Maturity of use in materials. *Source: F.R.D for the ADEME*

Available fibres with proven material upgrade potential: these are produced in large quantities using industrial production facilities.

Emerging fibres: these have potential; facilities and material applications are developing.

Potential fibres: exist in large quantities, but have not been harvested yet; the potential is unknown, but appears to be interesting

4. Getting the most out of flax and hemp fibres

The initial process applied to flax and hemp straw eliminates things like the seeds, powders from chaff and outer stem fragments, and the shive aggregates. This operation also produces fibres (length of fibres measuring in the decimetres, see also Chapter 2) and raw tows or scutching tows (fibre length measuring in the centimetres or millimetres), for the following markets:

- Automotive
- Building and construction
- Energy
- Horticulture
- Fertilisation
- Paper industry
- Textile/ Technical textile.

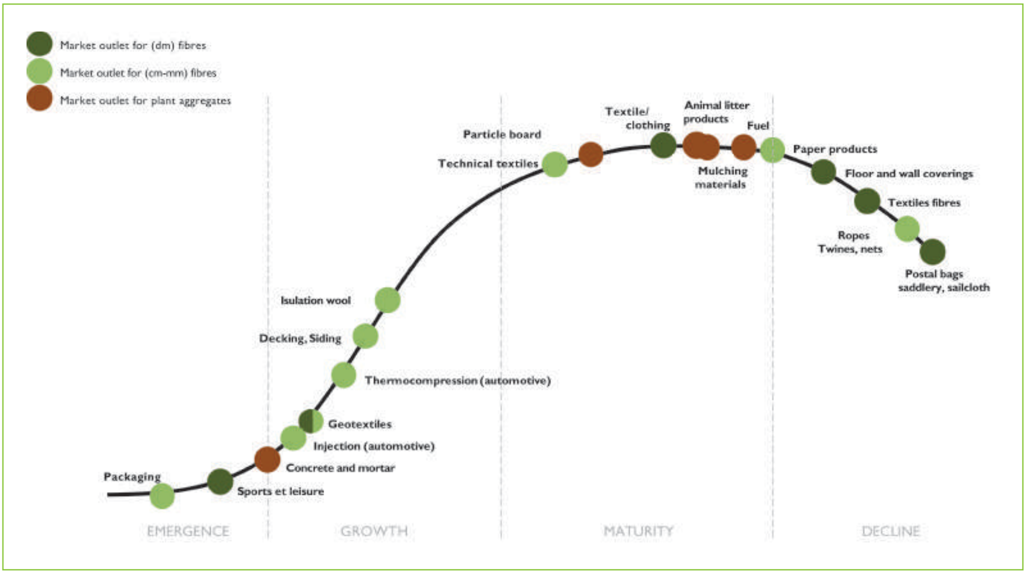

Figure 4: The high-potential markets for flax and hemp fibres are mostly in their emergent and growth stages. ***Source: F.R.D for the ADEME***

5. An available resource: France as an example

Based on figures for the 2001-2008 period, the current average production of flax and hemp plants in France guarantees 96,000 ha per year, or more than 600,000 tonnes of straw – enough for current material uses. This substantial production breaks down as follows:

- 93,000 t (dm) fibres;
- 76,000 t (dm-cm) fibres;
- 330,000 t aggregates;
- 60,000 t powders.

Fibres measuring in the decimetres (dm) and centimetres (cm) are obtained from the generic flax and hemp fibre extraction process, which is the first mechanical step to convert the plant into fibres. The flax fibres in the plant stalk (straw) are extracted through a beating process or decortication step, called scutching, to separate the woody material from the bast fibres, resulting in 93,000 t (dm) fibres and 76,000 t (dm-cm) fibres.

The dm scutched fibres are then further refined by hackling and combing, resulting in 65,000 t (dm) hackled fibres and 28,000 t of (dm-cm) hackling fibres. Figure 6.

The second and third converting steps consist of the fibre forming, spinning, and weaving processes and nonwoven manufacturing.

The **aggregates**, or the woody parts of the stalk, are separated out during the decortication step. The particle size varies (mm to cm) as a function of the specific defibrated plant and its quality, of the process used, and of the specifications.
The **powder** consists of all the residues from the first converting process on the straw. These residues comprise the plant binder substances (pectins), fibre particles, tow, and shives from the defibrating process. Figure 6.

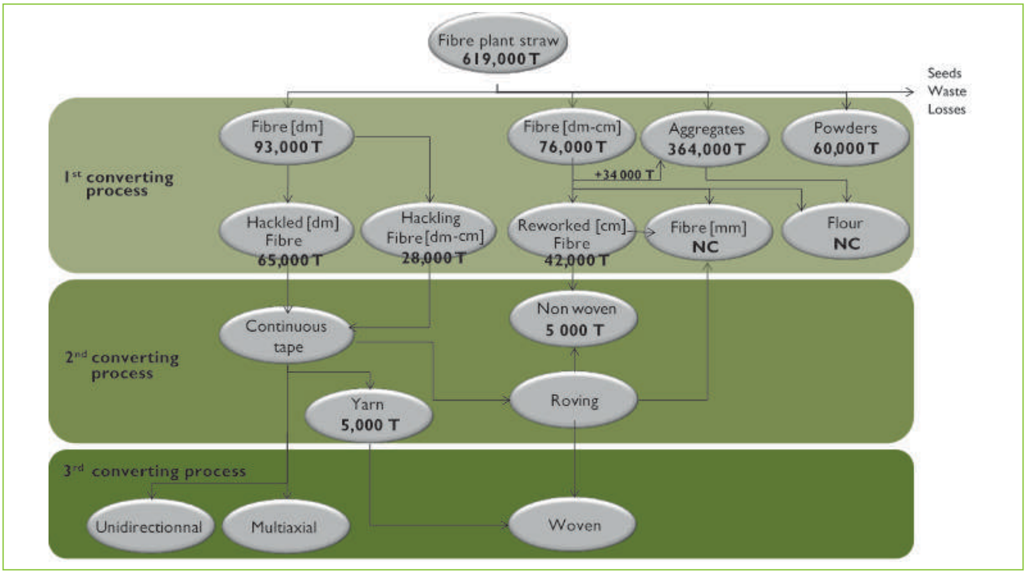

Figure 5: Simplified diagram for the plant fibre chain (2001-2008). ***Source: F.R.D for the ADEME***

Europe has a large, reliable supply of plant fibres that are produced in highly structured agro-industrial chains.

Availability as plant-fibre textile preforms

Several different technological processes are used to form plant fibres, including spinning, weaving (textile or technical) and specific treatments. Spinning can be used to mix fibres with different and/or complementary properties to create hybrid yarns. Weaving is an interlacing technique used to create fabrics for textile or technical uses.

- Technical textiles (or fabrics) are defined as any textile product or material for which the technical performance and functional properties are given priority over aesthetic or decorative characteristics. Technical textiles are characterised and designed for and as a function of the end use.

- 3D textiles consist of discontinuous fibres or continuous yarns placed spatially so as to create volumes with thick three-dimensional walls. Different 3D technologies have been developed to achieve the desired final shape: weaving, braiding, knitting, and non-woven techniques.

- Specific treatments have also been developed, e.g. finishing, coating, prepreg treatment, lamination, adhesive pretreatment, dyeing, printing, and sizing.

The 96,000 hectares account for only 0.3% of French usable agricultural area (UAA) and 0.05% of European UAA. So, the area represented by fibre plants is negligible when compared to other types of agricultural production. Over the course of history, the number of hectares devoted to fibre plants has developed as a function of demand and market prospects, rising from under a thousand to more than 200,000.

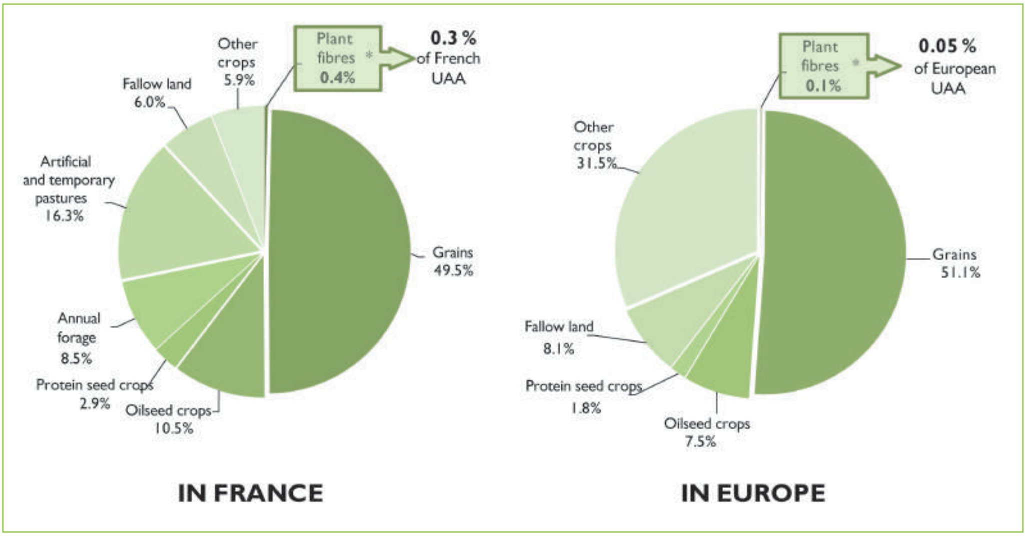

Figure 6: Distribution of usable agricultural area in France and in Europe.
Source: F.R.D for the ADEME

6. Increasing yields

Over the past 19 years, the average yield of straw for flax and hemp has been around 7 t/ha. A 13% variability from year to year (approximately 0.8T/ha per year) and a 5% upward annual trend were observed for that period. The yield of flax and hemp culture is very similar (6.9 and 7 t/ha, respectively), and also the total yield in fibres (dm plus dm-cm) is very similar. However, the flax industry generates a substantial amount of long fibres (15 to 25%).

The work of a variety of developers and technical institutes has contributed to increase the straw yield by 5-10% and the fibre content by 20-30% over the past 20 years.

	Straw	Fibres [dm]	Fibres [dm-cm]	Aggregates	Powders
Hemp	7 t/ha	-	**29-32%** 2.0 à 2.2 t/ha	**55%** 3.9 t/ha	**10-15%** 0.7 à 1.0 t/ha
Flax	6.9 t/ha	**15-25%** 1.0 à 1.7 t/ha	**10-15%** 0.7 à 1.0 t/ha	**45-50%** 3.1 à 3.5 t/ha	**10%** 0.7 t/ha

Figure 7: 2011 F.R.D study on conjectural yields.

7. Secure supply

Flax and hemp manufacturers and subsectors use a number of operational techniques to secure a reliable supply:

- **Contractual agreements**: stakeholders commit to specific volumes, prices and qualities
- **Co-partnerships**: bringing in fibre producers as partners
- **Buffer stocks**: safety inventories to guarantee a reliable supply in terms of available volumes and fibre quality
- **Multi-supplier resources**: increasing the number of fibre supply outlets cuts down on dependence and lowers risk, and can even push suppliers to compete.

The industry's players have set up very specific supply strategies to guarantee all stakeholders the agreed-upon volumes, prices and quality.

8. Production and supply capacities in line with demand outlook: the example of France

Forecast studies have indicated that fulfilling the needs for plant fibre and aggregate for material uses over the next 25 years would require around 300,000 hectares over the medium and long term (source: French Energy Conservation Agency ADEME). Even if the purpose of these studies was never to predict the evolution of markets over the coming years, it is still worthy of note that the plant fibre sector does have the capacity to increase production in response to a hypothetical surge in demand in the short, medium or long term.

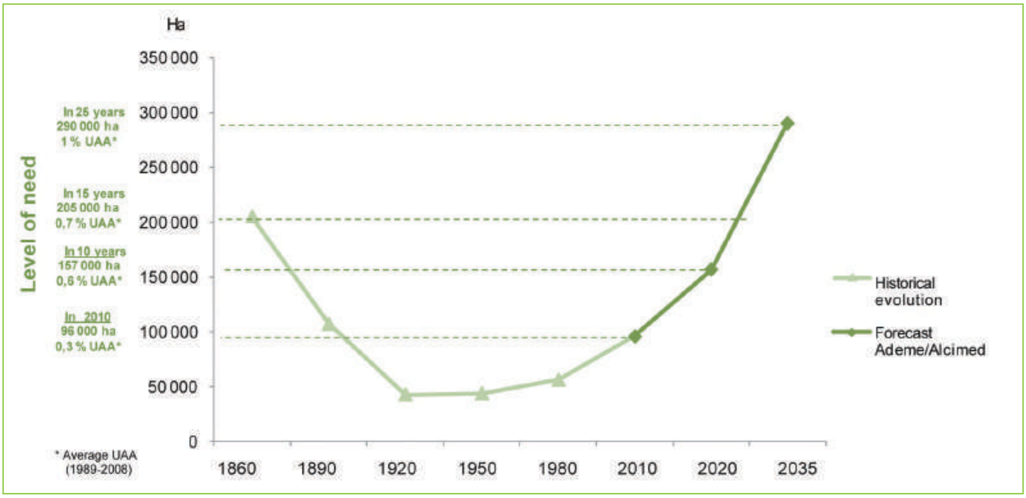

Figure 8: Evolution of actual and projected cultivation area for fibre plants (1860-2035).
Source: F.R.D for the ADEME

Rational mobilisation

So according to the ADEME's forecast, market needs would require mobilising around 300,000 hectares of fibre plants, compared to the 96,000 ha that are currently planted each year. This shift in scale needs to be put into perspective in light of the following:

300,000 ha is equivalent to:

- 1% of the usable agricultural area for the past 20 years;
- 1 year of average variability for French grain-planted area over the past 20 years;
- 2 years of average variability for the area devoted to the main spring break crops over the past 20 years;
- 20% of the cumulated increase of forest area over the past 20 years;
- 27% of the average annual area left fallow over the past 20 years;
- 150% of France's area planted in flax and hemp in 1852 (205,693 ha) at a period when food issues were paramount;
- the area needed to supply two French diester biofuel plants (*source: Saipol-Diester*).

Structurally speaking, the main driver for increasing the production of fibre plants is their upgradability, although there are three others that could be mobilised: in the short term, the current production basins; in the medium term, the creation of new basins; and over the long term, advances in varietal selection, or even the hypothetical use of new resources. (development of the plant's co-products)

Increasing area under cultivation

The prospects of growth in demand will entail significant and long-term changes to the areas under cultivation, and the flax and hemp industries have a solution. Due to the way the industry is organised, increasing flax and hemp production in the existing production basins would be rapidly feasible. These basins are structured around the farmers who deliver their crops to a fibre processor. They benefit from a number of years of experience, industrial organisation, qualified farmers who have the necessary harvesting machinery and storage capacity, and agronomical support services for new producers. Production can be adapted to increase the productivity per hectare, the area farmers devote to fibre plants, or the number of farmers who cultivate fibre plants.

Optimising yields

These past 20 years of research on flax fibre and hemp have produced an average of 5-10% increase in the straw yield and a 20-30% increase in the fibre content. If one takes into account a steady, similar genetic progress over the next 20 years, average straw yield for the main fibre plants (fibre flax and hemp) could amount to about 7.7 t per hectare in 20 years, or a 10% increase over current average yields. With respect to the current area under cultivation, that would represent an increase of nearly 60,000 t of fibre plant straw over the current volumes (51,500 t of flax fibre straw and 6,000 t of hemp straw).

Based uniquely on the current area under cultivation, genetic progress is a major driver that could contribute to increase the plant fibre supply by about 25% in 20 years. Added to a reasonable increase in the area under cultivation, this optimisation would enable matching supply to future surges in demand.

Highly stable prices

In addition to the capacity of the flax/hemp sector to meet the requirements of secondary processing industries, these plant fibres benefit from steady purchase prices over the long term, compared to other fossil-based raw materials.
Thanks to flax and hemp fibres, material manufacturers can reduce their oil dependence even more.

9. Reference

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* Agence de l'Environnement et de la Maîtrise de l'Energie, France

** Fibres Recherche Développement®, France

- XI - Keywords on natural fibre composites

Joris Van Acker,
Head Prof. at the The Laboratory of
Wood Technology of the Ghent University, Belgium

Color code refers to 5 topics:

(natural) fibres — polymer technology — composite technology — mechanical properties — environmental aspects

ADDITIVE: *additif (FR) / Additiv (G) / additief (NL) / additivo (I)*

Any substance added to another substance, usually to improve properties, such as plasticizers, compatibilizers, initiators, coupling agent, (light) stabilizers, anti-oxidants and flame-retardants.

BAST FIBRE: *Fibre libérienne (FR) / Bast (G) / bast (NL) / fibra di tiglio (I)*

The durable, nonliving sclerenchyma fibre in the phloem (bast), providing support to the plant. Well known bast fibres are flax, hemp, jute and ramie.

BIODEGRADABILITY: *biodégradabilité (FR) / Biodegradierbarkeit (G) / biodegradeerbaarheid (NL) / biodegradabilità (I)*

The natural decomposition capacity of organic matter. It is the ability of a molecule to be biologically degraded. It can be evaluated in terms of the degree of decomposition of a substance and the time necessary to achieve this decomposition.

BIODEGRADATION: *biodégradation (FR) / biologischer Abbau (G) / biodegradatie (NL) / biodegradazione (I)*

The decomposition, or the degradation of organic matter by the enzymatic action of micro-organisms (bacteria, fungi, algae). It involves fragmentation with chemical modification and loss of mechanical properties. The material is converted to carbon dioxide (CO_2), water (H_2O), and/or methane (CH_4), and possibly new biomass and residues.

BIOPOLYMER: *biopolymère (FR) / Biopolymer (G) / biopolymeer (NL) / biopolimero (I)*

Polymer of natural origin. Complementary: a biobased polymer is built on monomers of natural origin.

BRAIDED FABRIC: *cannevas tressé (FR) / Geflecht (G) / gevlochten stof (NL) / tessuto intrecciato (I)*

Fabric with a longitudinal yarn which can be 'threaded' between the two braided yarns.

BRAIDING, PLAITING: *tressage (FR) / flechten (G) / vlechten (NL) / intrecciare (I)*

The process of interlacing three or more threads in such a way that they cross one another in diagonal formation. Flat, tubular or solid constructions may be formed in this way.
Note: Tubular fabrics made by this process may be constructed with or without core, gut, filler, or stuffing threads, which when present are not interlaced in the fabric.

BREAKING: *broyage (FR) / brechen (G) / brakelen, breken (NL) / frantumazione (I)*

Leading a retted flax or hemp stem between fluted rollers in order to break the woody core of the stem into shives.

CARDING, ROLLER CARDING: *cardage (FR) / kardieren, krempeln (G) / kaarden (NL) / cardatura (I)*

The process of untangling and partially straightening fibres by passing them between two closely spaced surfaces which are moving at different speeds, and at least one of which is covered with sharp points, thus converting the flock (tangled mass of fibres) to a planar web.

CELLULOSE: *cellulose (FR) / Zellulose (G) / cellulose (NL) / cellulosa (I)*

(1) A polysaccharide consisting of a linear chain of β (1→4) linked D-glucose units: $(C_6H_{10}O_5)$ n.
(2) The fibrous carbohydrate found in the cell walls of green plants, some algae and oomycetes. It provides strength and rigidity to plant cells.

COMBING: *peignage (FR) / kämmen (G) / kammen (NL) / pettinatura (I)*

The first spinning operation, is increasingly done by scutchers. The combed fibre bundles, untangled and refined, are overlapped to form a soft, lustrous, continuous sliver ribbon which is ready for spinning.

COMPOUND: *fibres courtes imprégnées (FR) / Verabeitungsfertige Kunststoffmischung (G) gebruiksklaar kunstopfmengsel (NL) / composito (I)*

A "prepreg" of short fibres is called compound.

COPOLYMER: *copolymère (FR) / Copolymer (G) / copolymeer (NL) / copolimero (I)*

Polymer with two or more different monomer motifs.

COUPLING AGENT: *agent de couplage (FR) / Haftvermittler (G) / koppelingsreagens (NL) / agente legante (I)*

Any chemical substance designed to react with both the reinforcement and matrix phases of a composite material to form or promote a stronger bond at the interface; a bonding link.

CREEP: *fluage (FR) / Kriechen (G) / kruip (NL) / scorrimento (I)*

The irreversible deformation of a material under constant load for a given temperature.

ECO-DESIGN: *éco-conception (FR) / Ecodesign (G) / eco-design (NL) / eco-design (I)*

A product development method which integrates the environment from the design of products in order to reduce environmental impact.

ELASTICITY: *élasticité (FR) / Elastizität (G) / elasticiteit (NL) / elasticità (I)*

The property of a material which allows it to recover its original size and shape immediately after removal of the stress causing deformation.

ELASTOMER: *élastomère (FR) / Elastomer (G) / elastomeer (NL) / elastomero (I)*

Polymer with high molecular weight and a small number of cross-links between chains (1% of the monomers are linked) resulting in a highly deformable network.

ELEMENTARY FIBRE: *fibre élémentaire (FR) / Einzelfaser (G) / elementaire vezel (NL) / fibra elementare (I)*

Single plant cells, mostly between 10 and 25 µm thickness and between 20 and 50 mm length.

EXTRUSION: *extrusion (FR) / Extrusion (G) / extrusie (NL) / estrusione (I)*

Method of forming plastics by means of forcing molten resin through a shaped die, producing a constant-area cross section.

FABRIC: *tissu (FR) / Textilgefüge (G) / stof, legsel (NL) / tessuto (I)*

A material constructed of interlaced yarns, fibres or filaments. Used interchangeably with «cloth».

FATIGUE: *fatigue (FR) / Ermüdung (G) / vermoeiing (NL) / fatica (I)*

Damage or failure of a material under repeated applications of stress. Fatigue tests measure a material's ability to resist damage, which eventually causes failure.

FIBRE: *fibre (FR) / Faser (G) / vezel (NL) / fibra (I)*

The major reinforcement material component in a composite matrix. Often, fibre is used synonymously with filament fibre (synonym for endless fibres).

FIBRE BUNDLE: *faisceau de fibres (FR) / Faserbündel (G) / vezelbundel (NL) / fascio di fibre (I)*

Coarse, ribbon-shaped entities as they are isolated from the stem by breaking and scutching, consisting of a large number of single fibres in diameter.

FIBRE CONTENT: *proportion de fibres (FR) / Fasergehalt (G) / vezelgehalte (NL) / contenuto di fibre (I)*

The amount of fibre present in a composite. This is usually expressed as a percentage volume fraction or mass fraction of the composite.

FIBRE SATURATION POINT (FSP): *point de saturation des fibres (FR) / Fasersättigungspunkt (G) vezelverzadigingspunt (NL) / punto di saturazione della fibra (I)*

The point in drying wood or other lignocellulosic materials like natural fibres at which all free moisture has been removed from the cell itself while the cell wall remains saturated with absorbed moisture.

FRACTURE TOUGHNESS: *ténacité, résistance à la propagation de fissure (FR) / Bruchzähigkeit (G) breukvastheid (NL) / tenacità (I)*

A generic term for the measure of the brittleness of a material. Resistance to catastrophic or controlled extension of a crack.

GLASS FIBRE: *fibre de verre (FR) / Glasfaser (G) / glasvezel (NL) / fibra di vetro (I)*

A fibre pulled (spun) from an inorganic product of fusion which has cooled to a rigid condition without crystallizing. The silicate amorphous fibre consists of, depending on the application, a mixture of silicic acid and metal oxides.

GLASS TRANSITION (TEMPERATURE): *(température de) transition vitreuse (FR) Glasübergangs-(temperatur) (G) / Glastransitie-(temperatuur) (NL) (temperatura) transizione del vetro (I)*

Reversible change in an amorphous polymer or amorphous regions of a partially crystalline polymer from or to a viscous, rubbery, or hard and relatively brittle condition.

HACKLING: *peignage (FR) / hecheln (G) / hekelen (NL) / pettinatura (I)*

The further cleaning of the fibre bundles after scutching, to remove any remaining shive and separate them into much finer bundles referred to as technical fibres.

HARDENER: *durcisseur (FR) / Härtungsmittel (G) / verharder, hardingsmiddel (NL) / indurente (I)*

A substance or mixture added to a thermoset plastic composition to promote or control the curing action by taking part in it.

HARDWOOD: *bois feuillu (FR) / Laubholz (G) / loofhout (NL) / legno di latifoglie (I)*

Wood originating from angiosperms, also called broadleaved trees, examples are beech, oak, poplar,...

HEMICELLULOSE: *hémicelluloses (FR) / Hemizellulose (G) / hemicellulose (NL) / emicellulosa (I)*

Class of plant cell wall polysaccharide that cannot be extracted from the wall by hot water or chelating agents, but can be extracted by aqueous alkali. Includes xylan, glucuronoxylan, arabinoxylan, arabinogalactan II, glucomannan, xyloglucan and galactomannan. Part of the cell wall matrix. A polysaccharide found in plant cell walls.

HOMOPOLYMER: *homopolymère (FR) / Homopolymer (G) / homopolymeer (NL) / omopolimero (I)*

Polymer based on a monomer with identical motifs.

HYBRID: *hybride (FR) / Hybrid (G) / hybride (NL) / ibrido (I)*

A composite laminate consisting of two or more composite material systems. Two or more different fibres, such as flax and glass, combined into a structure.

INCINERATION: *incinēration (FR) / Verbrennung (G) / verbranding (NL) / combustione (I)*

Consists of burning waste in ovens at temperatures between 700°C and 900° C.

INJECTION MOLDING: *moulage par injection (FR) / Spritzgießen (G) / spuitgieten (NL) / stampaggio a iniezione (I)*

Method of forming a plastic to the desired shape by forcibly injecting the polymer into the mold.

INTERFACE: *interface (FR) / Grenzschicht (G) / raakvlak (NL) / interfaccia (I)*

The boundary or surface between two different, physically distinguishable media. On fibres, the contact area between fibres and sizing or finish. In a laminate, the contact area between the reinforcement and the laminating resin.

INTERPHASE: *interphase (FR) / Zwischenphase (G) / interfase (NL) / interfase (I)*

Narrow region which results from the chemical reaction between the matrix and the fibre surface. Interface is the idealized description of the interphase.

KINK-BAND: *bande de plissement (FR) / Kink, Knick (G) / afschuifband (NL) / nastro di piegatura (I)*

A localised flax fibre defect having an impact on the micromechanics.

KNITTED FABRIC: *tissu tricotē (FR) / Gestrick (G) / breisel (NL) / tessuto a maglia (I)*

A fabric produced by the intermeshing of loops of yarns, resulting in continuously varying fibre orientations.

LAY-UP: *moulage au contact (FR) / Handlaminierverfahren (G) / handlaminatie (NL) / stampaggio per contatto (I)*

The process of placing the reinforcing material in position in the mold.
An alternative definition: a description of the component materials, geometry, and so forth, of a laminate.

LIFE CYCLE ANALYSIS (LCA): *analyse du cycle de vie (FR) / Lebenszyklusanalyse (G) levenscyclusanalyse (NL) / analisi del ciclo di vita (I)*

A global, multi-criteria tool for ecodesign which enables the environmental impacts of a product or system to be quantified.

LIGNIN: *lignine (FR) / Lignin (G) / lignine (NL) / lignina (I)*

Organic substance which act as a binder for the cellulose fibres in wood and certain plants and adds strength and stiffness to the cell walls. The chemical structure of lignin is composed of a complex polymer of phenylpropanoid subunits, laid down in the walls of plant cells such as xylem vessels and sclerenchyma. It imparts considerable strength to the wall and also protects it against degradation by microorganisms. It is also laid down as a defence reaction against pathogenic attack, as part of the hypersensitive response of plants. A complex polymer; the chief non-carbohydrate constituent of wood; binds to cellulose fibres to harden and strengthen cell walls of plants. A compound found in cell walls, and this non living component provides a structural function in xylem and bark in plants.

MATRIX: *matrice (FR) / Matrix (G) / matrix (NL) / matrice (I)*

The material in which the fibre reinforcements of a composite system are embedded.
Thermoplastic and thermoset resin systems can be used, as well as metal and ceramic.

MOISTURE ABSORPTION: *absorption de l'eau (FR) / Feuchteabsorption (G)*
vochtabsorptie (NL) / assorbimento dell'umiditā (I)

(1) The amount of water absorbed by a composite material when immersed in water or exposed to humidity for a stipulated period of time.
(2) The ratio of the weight of water absorbed by a material, to the weight of the dry material. All organic polymeric materials will absorb moisture to some extent resulting in swelling, dissolving, leaching, plasticizing and/or hydrolyzing, events which can result in discoloration, embrittlement, loss of mechanical and electrical properties, lower resistance to heat and weathering and stress cracking.

MOLD: *moule (FR) / Werkzeugform (G) / mal, matrijs (NL) / stampo (I)*

The cavity or matrix into or on which the plastic composition is placed and from which it takes form. The tool used to fabricate the desired part shape.

MONOMER: *monomère (FR) / Monomer (G) / monomeer (NL) / monomero (I)*

Simple molecules which can be assembled together into polymers. Monomers have low molecular weights.




NATURAL FIBRE: *fibre naturelle (FR) / Naturfaser (G) / natuurlijke vezel (NL) / fibra naturale (I)*

Fibre derived from plants or animals (organic) and also comprising e.g. asbestos (inorganic).

NON-CRIMP FABRIC: *tissu multiaxial (FR) / Multiaxialgelege (G)*
niet ingeweven legsel (NL) / tessuto multiassiale (I)

Consists of different unidirectional fibre layers, each layer with their own direction, which are stitched together by means of very fine threads.

NONWOVEN FABRIC: *mat non tissé (FR) / Fasermatte (G) / gebonden textielvlies (NL) / tessuto non tessuto (I)*

A material formed from fibres or yarns without interlacing (e.g., stitched bonded, nonwoven broadgoods).

PECTIN: *pectine (FR) / Pektin (G) / pectine (NL) / pectina (I)*

Class of plant cell wall polysaccharide, soluble in hot aqueous solutions of chelating agents or in hot dilute acid. Includes polysaccharides rich in galacturonic acid, rhamnose, arabinose and galactose, for example the polygalacturonans, rhamnogalacturonans and some arabinans, galactans and arabinogalactans. Prominent in the middle lamella and primary wall.
Any of various water-soluble colloidal carbohydrates that occur in ripe fruit and vegetables; used in making fruit jellies and jams. A polysaccharide that can be found in a plants' cell wall.

PELLETISER: *granulateur (FR) / Pelletpresse (G) / pelletpers (NL) / pellettizzazione (I)*

Machine connected to the composite extruded strands to produce granulates of a specific size and fibre length.

PLAIN WEAVE: *Taffetas (FR) / Leiniwandgewebe (G) / vlakweefsel, lijnwaadbinding (NL) / taffetà (I)*

A weaving pattern where the warp and fill fibres alternate; i.e., the repeat pattern is warp/fill/warp. Both faces of a plain weave are identical. Properties are significantly reduced relative to a weaving pattern with fewer crossovers.

PLANT FIBRE: *fibre végétale (FR) / die Pflanzenfaser (G) / vezel van plantaardige oorsprong (NL) / fibra vegetale (I)*

A narrow, elongated, and thick-walled cell in sclerenchyma tissues of plants.

POLYMER: *polymère (FR) / Polymer (G) / polymeer (NL) / polimero (I)*

A long molecule made up of basic elements known as monomers joined together by covalent bonds. Often referred to with the terms resin or macromolecule indicating a long molecule made up repeating simple molecules (or monomers).

POLYMERIZATION: *polymérisation (FR) / Polymerisation (G) / polymerisatie (NL) / polimerizzazione (I)*

The reaction which results in, from the initial monomers, the formation of components with higher molecular weight, polymers or macromolecules. The polymers are usually based on carbon atoms (organic molecules) or silicon atoms (silicone polymers).

PREFORM: *préforme (FR) / Textiles Halbzeug (G) / preform (NL) / preformato (I)*

Consist only of the fibres, the matrix will be added during production of the composite.

PREPREG: *préimprégné (FR) / Vorimprägniertes Halbzeug (G) / prepreg (NL) / preimpregnato (I)*

The fibres are already pre-impregnated with the matrix. The impregnation of the wet prepreg is completed during manufacturing when the matrix (thermoset or thermoplastic) is consolidated.

PULTRUSION: *pultrusion (FR) / Strangziehen (G) / pultrusie (NL) / poltrusione (I)*

Method of manufacturing composites, by "pulling" fibre strands wetted with resin, through a heated die. Pultrusion is used to efficiently produce large amounts of a continuous profile.

RANDOM MAT: *fibres aléatoirement dispersées (FR) / Wirrfaservlies (G) / random mat (NL) / tessuto non tessuto (I)*

A non-oriented preform (textile structures: fleece or felt). **Equivalent: nonwoven.**

RELEASE AGENT: *agent de démoulage (FR) / Trennmittel (G) / ontmallingsproduct (NL) / prodotto di rilascio (I)*

Materials that are used to prevent cured matrix material from bonding to tooling.

RESIN: *résine (FR) / Harz (G) / Hars (NL) / resina (I)*

A material, generally a polymer that has an indefinite and often high molecular weight and a softening or melting range and exhibits a tendency to flow when it is subjected to stress. Resins are used as the matrices to bind together the reinforcement material in composites.

RESIN-TRANSFER MOLDING (RTM): *injection basse pression (FR) / Harzinjektionsverfahren (G) harsinfusie (NL) / infusione (I)*

A molding process in which catalyzed resin is transferred into an enclosed mold into which the fibre reinforcement has been placed; cure is normally accomplished without external heat. RTM combines relatively low tooling and equipment costs with the ability to mould large structural parts.

RETTING: *rouissage (FR) / rösten (G) / roten (NL) / macerazione (I)*

The first natural phase in the transformation from plant to fibre is provided by alternating rain and sun which allows the flax to ret. Thanks to the action of micro-organisms and bacteria naturally present in the soil, retting (from July to September) breaks down the pectin layer that binds the fibres to the woody part of the plant. To encourage uniformity in retting, the flax swaths are turned halfway through this process.




ROTARY KNEADING: *malaxage rotatif (FR) / Rotationskneter (G) / draaikneden (NL) / impastatura rotativa (I)*

Manufacturing process applying shear force and temperature are applied on the fibre as well as the molten thermoplastic matrix to ensure homogeneous distribution.

ROVING: *mèche (FR) / Roving (G) / lont, wiek (NL) / stoppino (I)*

A textile ribbon-shaped structure of endless glass fibres. Adapted to, for example, flax: Sliversor pre-yarns processed into a parallel ribbon-shaped structure with little or no twist.

SCUTCHING: *teillage (FR) / schwingen (G) / zwingelen (NL) / stigliatura (I)*

The flax fibre bundles are in the outer sheath of the stem. The fibres in the outer layer are stripped off as complete bundles and separated from the woody core (flax shives are used as wood chips for gardening, animal litter, particle board, etc.). Scutching is the second phase of transformation from plant to fibre, is done after harvesting/retting. A specialized mechanical process, its successive stages are rippling, drafting, breaking and threshing. The fibres are then classified in two categories: long fibres (line flax) and short fibres (tow).

SHEAR STRENGTH: *résistance en cisaillement (FR) / Scherfestigkeit (G) / schuifsterkte (NL) / resistenza al taglio (I)*

The maximum shear stress that a material is capable of sustaining. Shear strength is calculated from the maximum load during a shear or torsion test and is based on the original cross-sectional area of the specimen.

SHIVES/CHAFF: *anas de lin, chènevotte de chanvre (FR) / Schäben (G)*
lemen, scheven (NL) / anas di lino, canapule (I)

In the decortication process this is the woody core material of the flax or hemp stem, which is broken away and mechanically separated from the fibre bundles.

SHORT FIBRE: *fibre courte (FR) / Kurzfaser (G) / korte vezel (NL) / fibra corta (I)*

Short fibres can be defined as being < 15 cm in length, commonly shorter than 2 cm (range dm – cm). Short fibres can for example be used in extrusion and injection moulding.
However, in the flax and hemp world, traditional short fibres are fibre bundles with a length up to 30 cm which are for the traditional wet spinning textile application already short.
Equivalent term: tow.

SLIVER: *ruban (FR) / Band (G) / band, lint (NL) / nastro (I)*

In general an assemblage of untwisted parallelised fibres or fibre bundles produced by a carding or combing machine and ready for drawing, roving, or spinning.

SOFTWOOD: *bois résineux (FR) / Nadelholz (G) / naaldhout (NL) / pianta aghifoglia (I)*

Wood originating from gymnosperms, also called coniferous trees, examples are pine, spruce,...

SPECIFIC STIFFNESS: *rigidité spécifique (FR) / spezifische Steifigkeit (G)*
specifieke stijfheid (NL) / rigidità specifica (I)

The stiffness divided by the specific weight (or density).

SPINNING: *filature (FR) / spinnen (G) / spinnen (NL) / filare (I)*

The process of creating yarn (or thread, rope, cable) from various raw fibre materials.

STIFFNESS: *rigidité (FR) / Steifigkeit (G) / stijfheid (NL) / rigidità (I)*

The relationship of load to deformation; a term often used when the relationship of stress to strain does not conform to the definition of Young's modulus.

STRAND, THREAD: *fil (FR) / Kabel, Faden (G) / streng, draad (NL) / filo (I)*

In general an assemblage of untwisted continuous (endless) fibres.

STRENGTH: *résistance à rupture (FR) / Festigkeit (G) / sterkte (NL) / resistenza alla rottura (I)*

The ability of a material to withstand an applied stress without failure. It is not just about breaking, but is often also to do with resistance to permanent deformation.

SYNTHETIC OR MAN-MADE FIBRE: *Fibre synthétique (FR) / Chemiefaser (G)*
synthetische vezel (NL) / fibra sintetica (I)

Fibre that start from a chemical solution. Also a natural product can be processed to create a synthetic fibre.

TECHNICAL FIBRE: *fibre technique (FR) / technische Faser (G) / technische vezel (NL) / fibra tecnica (I)*

Thin long fibre consisting of several, commonly 10 to 40 elementary fibres in diameter, which is the product from hackling the fibre bundles.

TEX:

A unit for expressing linear density, equal to the mass in grams of 1 km of yarn, filament, fibre or other textile strand (1 tex = 1g/1,000m).

THERMOPLASTIC POLYMER: *polymère thermoplastique, thermoplaste (FR) / Thermoplast (G)*
thermoplast (NL) / termoplastico (I)

Consist of long molecules (molecular chains with strong covalent bonding) connected together by weak (secondary) bonds (van der Waals and hydrogen bonds).

THERMOSETTING POLYMER: *polymère thermodur, thermodurcisseur (FR) / Duroplast (G)*
thermoharder (NL) / duroplast (I)




Consist of short molecular chains linked by strong covalent (primary) bonds to form a three-dimensional network (densely cross linked) which is insoluble and does not melt before degrading when heated.

TOW: *étoupe (FR) / Werg (G) / klodden (NL) / stoppa (I)*
Short fibre (shorter than 30 cm) obtained during the scutching or hackling process of flax.

TRANSVERSAL STIFFNESS: *rigidité transverse (FR) / transversale Steifigkeit (G)*
transversale stijfheid (NL) / rigidità trasversale (I)

The stiffness under a stress which is perpendicular to the fibres (is far less than the longitudinal stiffness).

TWIST: *torsade (FR) / Drehung (G) / torsie (NL) / torsione (I)*

Yarn twist is the measure of the spiral given to a yarn in order to hold the constituent fibres (S or Z yarn) or threads (e.g. S or Z twine) together. Yarn has S twist if when held in a vertical position the visible spirals or helices around its central axis are in the direction of slope of the central portion of the letter S. Z twist is in the other direction.

UNIDIRECTIONAL (UD): *unidirectionnel (FR) / uindirektional (G) / unidirectioneel (NL) / unidirezionale (I)*

Refers to fibres that are oriented in the same direction, such as unidirectional fabric, tape, or laminate.

WEAVE: *tissage (FR) / Gewebe (G) / weefsel (NL) / tessitura (I)*

Pattern by which a fabric is formed from interlacing yarns. In a plain weave, the warp and fill fibres alternate to make both fabric faces identical. In a satin weave, the pattern produces a satin appearance with the warp yarn crossing over several fill yarns and under the next one (e.g., eight-harness satin would have warp yarn over seven fill yarns and under the eighth).

WEFT: *trame (FR) / Schussfaden (G) / weefpatroon (NL) / trama (I)*

The system of yarns running crosswise in a fabric. Also known as fill. This is the yarn which is drawn through the warp.

WOVEN FABRIC: *tissu (FR) / Gewebe (G) / weefsel (NL) / tessuto ortogonale (I)*

Fabric with warp and weft yarns form a 90° angle to another. Hence it consists of interlaced yarns in 2 directions.

YARN: *fil (FR) / Garn (G) / garen (NL) / filato (I)*

An assemblage of twisted filaments, fibres, or strands, either natural or man-made, to form a continuous length that is suitable for use in weaving or interweaving into textile materials.

YOUNG'S MODULUS: *module de Young (FR) / Elastizitätsmodul (G) / elasticiteitsmodulus (NL) / modulo di Young (I)*

The ratio of normal stress to the corresponding strain for tensile or compressive stresses less than the proportional limit of the material.

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APPENDIX - I

Other technical applications of Flax and Hemp

Considered to be the oldest textile fibre in the world, flax has always been known for its sturdiness. As early as the Pharaonic Age in Egypt, flax was used to make ropes, boat sails, and linen for clothes. In the twentieth century, new applications for flax emerged out of farm mechanisation, variety creation, and the perfecting of scutching and hackling methods. These days, both farming and processing are industrialised. Flax is still prized for its traditionally refined yet natural characteristics, but now also for its new performance properties developed by the industry's research and development services.

1. Textile applications for flax

There is a wide range of markets for flax, including clothing, household linens, postal bags, twines, and even fire hoses. Clothing applications account for 70% of the flax fibre used. Household linens come next with 15%, followed by decoration, wall coverings and furnishing fabrics (10%), and technical fabrics (5%).

Flax properties in textile applications

100% flax rug
(Source: *Secrets of Linen*)

Flax is prized for its fibre properties. Flax fibres make high-quality, defect-free textiles that are wear-resistant without stretching or shedding. Thanks to its hollow fibres, textile flax "breathes" and provides excellent insulation in any season, helping to regulate the body temperature. Linen is cool to wear in the summer, yet also comfortable in the winter.
Flax can absorb up to 20% of its dry weight in moisture without feeling damp to the touch, which is a special advantage for household linens. Non-allergenic and antibacterial (some surgical sutures are made of flax), flax is hygienic and comfortable against the skin, which is why it is used for bed linens. Known for its affinity for dyes, flax makes it possible to obtain wide ranges of subtle shades of colour, using less dye. The sturdiness of the linen fabrics used in furnishings is highly appreciated, especially for seat covers. The antistatic properties of flax give curtains, wall coverings and rugs that do not attract dust.

Innovations

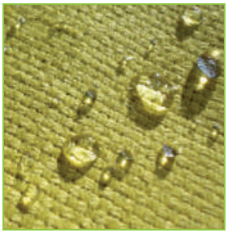
Constant R&D on the part of European scutchers, spinners, weavers and knitters gives us linen fabrics that are opening up new textile market prospects, from ready-to-wear clothing to household goods. Thinner than ever for the same strength, flax fibre is appearing in new textile applications:

Technical properties in flax textile applications:
- Strength
- Breathability, heat regulation
- Absorbency
- Easy maintenance
- Hypoallergenic, antibacterial
- Curative

Eco-finishes are the focus of exclusive new developments. The GOTS (Global Organic Textile Standard) and OEKOTEX seals of approval are given priority: low-impact reactive dyes, eco wrinkle-resistance treatments and enzyme finishes are responses to demand for optimally eco-designed textiles.

Source: *Le Coq Sportif & Linen Dream Lab*

In addition to the usual perpendicular warp and weft yarns, different versions of the linen stitch are developing, with a range of gauges down to extra-fine, with straight or circular weaves for new uses, in jersey or fleece with the same heat-insulating properties as synthetic fleece fibre. With a waterproof coating, linen is also suitable for outdoor and even baggage applications.



Outdoor textiles: rain repellent, waterproof, UV proof

A UV-proofing treatment makes linen perfectly resistant for outdoor use.

Fire resistant linen

Although not highly flammable, linen textiles need to be treated when used in public spaces to comply with fire regulations in many countries. Several types of flame-retardant treatments, tested on linen to match the standards for public spaces, are available, including new eco-friendly treatments. The choice will depend on final use (curtains, upholstered furniture, etc.) and care (dry-cleaning or machine washing).

2. Eco-construction & Home furnishings

The building sector is a particularly dynamic emerging market for hemp fibre applications. Sustainable (eco) construction and home furnishings account for a 10% share of the hemp market.

Technical advantages of flax and hemp fibres for substainable construction and home furnishings :

- Hygienic product
- High heat and sound insulation properties
- Breathability/permeability to water vapour
- Naturally repels insects and other pests
- Easy transport and implementation
- Stores CO_2
- Comfortable installation with no risk of irritation for skin or eyes
- Zero waste, upgradability of all plant co-products

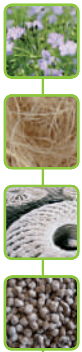
Hemp concrete blocks

Hemp concrete and mortar are organic composites made of water with lime as a binder, and hemp aggregate. This mixture is cold-pressed into blocks and open-air dried. Walls built of hemp concrete blocks on a wood frame store from 14 to 35 kg of CO_2 equivalent per m² [1].

- The blocks are fire resistant and permeable to water vapour, creating a hygienic, non-allergenic environment.

- They guarantee good acoustic correction. The insulating coatings used make the rooms especially comfortable because they improve surface heat transfer.*

1 Source L.C.D.A



Because it is renewable, hemp is becoming one of the most sought-after materials in the emerging eco-construction sector.

Source: *Chanvribloc*

Insulating wools

Insulating hemp or flax wools are already well known and in widespread use in attics, walls, floors and ceilings.

Natural insulation materials for housing is a relatively mature market that is growing by 40% or more per year in Europe.

Hemp and flax wools provide hygienic, environment-friendly heat and sound insulation for walls, ceilings and floors.

These fibres "breathe", so they help to regulate the flow of water vapour that arises from the differences in indoor and outdoor temperatures. This type of insulation absorbs moisture from the air and releases it to the exterior when the ambient humidity decreases.

Other advantages are that the fibres act as a natural repellent for moths and other insect pests, and they are indigestible for rodents.

Unlike glass fibre, these natural fibres will not irritate the skin or eyes during installation. They have a very low static charge and no electromagnetic current conductivity.

Source: *Soprema*

Roof deck protection – rain shield

This material with 75% natural flax fibre reinforcement is highly permeable to water vapour and extremely tear resistant. It won't tear when nails are used. Lightweight but not too flexible, it cuts down on noise pollution and does not have a typically synthetic odour.

Source: *Ecotechnilin*

Substrate for floor board

100% natural flax floor-board substrate is designed to enhance home comfort:

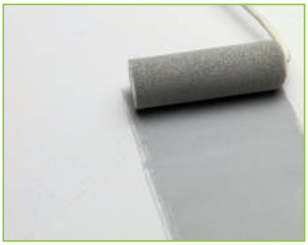
- Minimises impact noises
- Easy to implement
- Minimises noise of footsteps inside the room
- Smoothes out irregular undersurface
- Insect, mould and mildew proof
- Long-term acoustic damping

Source: *Entreprise De Sutters*

Flax or hemp particle board for walls, etc.

Flax shives or hemp chaff are used to make lightweight yet sturdy particle board that is perfect for walls, door cores, or counters. These are machined using the same tooling as wood particle board. In 22-mm or more thicknesses, they stay fire-resistant and flame retardant for at least 30 minutes, and can be mixed with wood fibre aggregates. The core of such panels consists of agglomerated lignocellulosic flax particles that are adhesive-bonded and pressed.

Flax shives



Source: *Libeco Lagae*

Technical fabrics

In wall applications as a substitute for glass fabric, 100% flax technical fabric has maximum dimensional stability and a uniformly absorbent surface. It requires no undercoat, and less paint to cover it.

Wall coverings

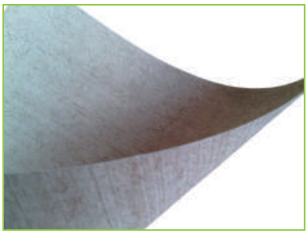
These natural-looking wall coverings in a range of subtle shades consist of a 100% flax layer bonded to paper made with pulp that also incorporates flax fibres.

Source: *Donghia*

Flax-fibre spunlace nonwoven fabrics

Source: *Texilis*

There are a number of potential applications for this wet-laid nonwoven material, e.g. indoor blinds, sunscreens, wall coverings, stretch ceilings, signs, shoe soles, and tablecloths, as a function of how the material is treated (non-combustible treatment, water proofing, colours, coatings, etc.) The fabric comes in a number of different areal weights from 80g/m² to 400g/m², in a width of 2.20 m. It can be reinforced with a textile grid and micro-perforated (80 to 110g/m²). No binders are incorporated into the fabric, it consists uniquely of flax fibres and viscose.



Source: *Texilis*

Source: *TDA Stores*

Optimum vibration damping and good heat/sound insulation are some of the advantages, thanks to the following properties (for a 65% flax/35% viscose fabric with an areal weight of 130g/m²): Filters out 98% of UV rays when used as blinds.

3. Horticulture

Used as mulch mats for green areas, e.g. along highways or for potted plants, these biodegradable nonwoven mats in flax or hemp felt constitute an effective and environment-friendly alternative to plastic sheets.

Advantages:

- Low water and fertiliser consumption
- Protection for young plants
- Stable soil temperatures

Source: *Ecotechnilin*

Chaff of hemp and shives of flax are also used for horticultural mulch. They eliminate the need for manual or chemical weeding control and act as a screen to keep seeds from germinating. Their water absorption capacity cuts down on the need for watering, as the shives keep the ground damper for longer. The chaff's neutral pH is compatible with the pH of the soils, so as the chaff decomposes, it helps to enrich the soil.

Paper products

Flax tow and paper-industry hemp fibres are used to make special papers like cigarette papers, paper for bibles, bank notes, technical filter papers, newspaper, cardboard and packaging. The paper industry accounts for 70% of the hemp market.

Litter for animals

Animal litter accounts for 70% of the chaff market. Hemp chaffs and flax shives are upgraded into litter for poultry and horses, because they are much more absorbent than straw (4 times more for hemp and 2.5 times for flax) and need to be changed less often.

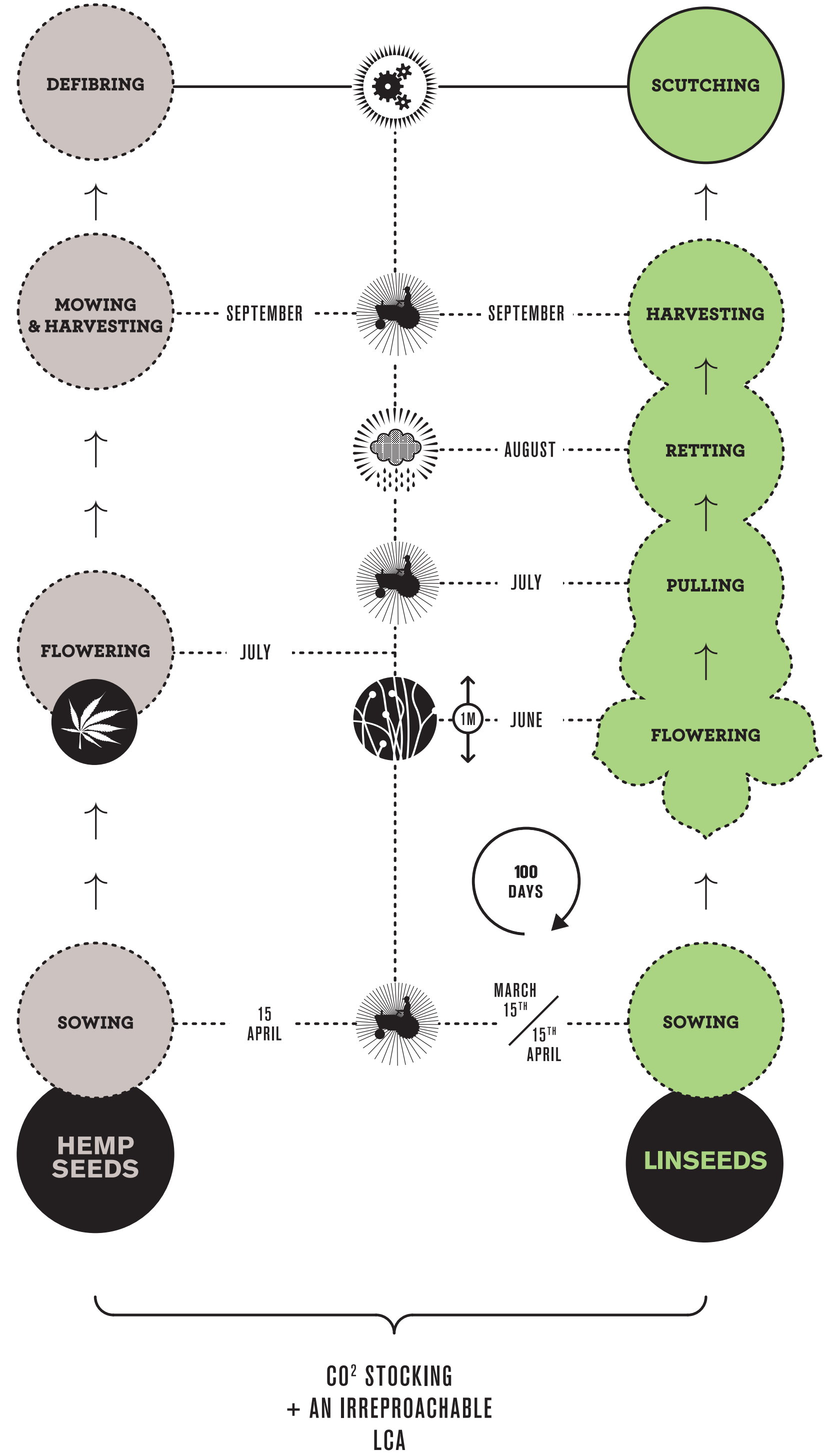
Biomass energy

Hemp and flax powders from the straw defibrating process are compressed and used to make briquettes. These 100% natural briquettes are produced mechanically, with no chemical additives. The potential applications are in biomass energy (dual fuel industrial boilers), industrial-scale or agricultural methanation, composting, and treatment of liquid effluents.




APPENDIX - II

Flax & Hemp growing, an ecological bonus



Growing flax and hemp.




Flax, a localized resource
Flax cultivation is strongly dependent on regional factors such as the specific geoclimate conditions and the local human skills.

Specific climate conditions for a flax-growing region

Europe provides a natural flax-growing region, where flax is cultivated on loamy soils that are swept by winds from the west, and where the plant properties are optimised in the moist, temperate ocean climate. The region stretches mainly along a wide coastal strip from Caen in Normandy, France to Amsterdam in Holland, with a “micro” region where the area facilitates management of the flax-fibre processing chain.

1. Green growth for flax and hemp

Ecosystem protection:
- A **carbon sink** in agricultural Europe
- **Zero waste** – all plant constituents are put to use!
- A **water-efficient** plant
- **No** soil or water **pollution**
- **Crop rotation** to regenerate the soil for the next crop

Crop rotation benefits soil conservation
Flax is grown in rotation with other crops for better soil regeneration. As observed in flax farming, extending the rotation periods in the use of alternating crops is a key element in new soil conservation practices to favour carbon storage in the soils.

Very low use of phytosanitary treatments
Totally absent in hemp cultivation, phytosanitary treatments are used sparingly in flax cultivation, which contributes, along with the longer crop rotation periods, to a global decrease in the use of such treatments in agriculture.

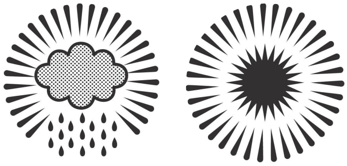
Cultivating without irrigation
The absence of irrigation lowers the pressure on agriculture in terms of water apportionment.

Nitrogen-efficient crops
Fibre plants are very nitrogen-efficient, which helps to reduce the primary source of greenhouse gas (GHG) emissions in agriculture.

Lowering GHG emissions
For 1 hectare of flax and hemp fibre plants in the European Union, the long-term carbon storage is estimated at 3.34 tonnes (t) of CO_2 equivalent. This is in connection with the share of production that is dedicated to perennial uses – in particular biomaterials for construction and plastics processing.

> “Concerning the environmental impact of flax and hemp cultures, the evaluation report underlines that these cultures clearly need less fertilizer and chemical pesticides than replacement cultures. In addition, they have positive effects on the agricultural eco-systems’ diversity and landscape. In this context, growing these fibers offers a welcome ‘environmental pause’ in order to maintain soil quality, preserve landscapes and encourage bio-diversity.”
>
> *Extract of the ADVISORY COMMISSION'S REPORT TO THE EUROPEAN PARLIAMENT. Brussels, May 20, 2008.*

2. Growing flax and hemp: area of technical skills



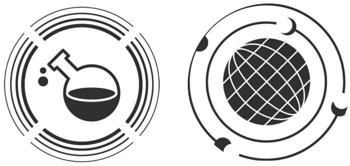
Converting process without the use of synthetic chemicals

Converting fibre plants is an environment-friendly process. Flax and hemp require neither energy nor solvents to be transformed into fibres, unlike for synthetic fibres. The fibres are retted directly in the farmer’s field to facilitate fibre extraction. The retting process involves balancing the right “dosage” of rainfall and sunshine, thereby setting the natural action of enzymes into motion to degrade the pectins that bind the fibres to the straw. The determining factor in proper control over this process and achieving uniform results is the knowledgeable judgement of the farmers themselves.

Managed mechanisation

The players in the European industry have unrivalled skills in the cultivation and primary processing of flax and hemp: added to their knowledgeable experience of natural processes and of how to put these to best effect are the proven technological capabilities of the harvesting machines. By harnessing such mechanization to a sound R&D strategy, the industry can add significant value and make the most of flax cultivation. The mechanical pullers, turnover machines and swath rollers used specifically by European flax growers are designed to ensure uniform fibre quality throughout the mechanical processing stages, from pulling to scutching to hackling.

Innovation all along the value chain



R&D investment in the flax and hemp industries covers all production stages. The synergy between specialist skills like varietal creation, expertise in the specific features of cultivation, optimisation of the mechanised extraction process, and production of semi-finished products works to structure a sustainable agro-industrial chain. The traceability of the flax and the hemp at every coordinated stage of production is a guarantee of uniform fibre quality and compliance with the specifications of manufacturers seeking renewably sourced fibres that are the result of tried-and-true agricultural skills.




The CELC Technical Section

Created in 2005, the CELC's Technical Section is a leading platform in the field of new technical applications for flax & hemp fibres in composites and eco-building.

The 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 industrialisation capacity for technical flax and hemp applications.

Its goals:

- Organise a European skills network that includes companies, universities and research centres
- Foster research by participating in European programmes
- Participate in European events and international tradefairs

With its European Scientific Committee, the CELC guides its members towards the future to discover new technical opportunities.

The Linen Dream Lab is a showroom dedicated to textile and technical innovations. It offers services to innovators in the fashion, art of living and design industries: support for creation and sourcing. It has material, yarn, and fabric libraries.

The European Confederation of Flax and Hemp (CELC) is the only European agro-industrial organization that encompasses all production and processing stages for flax & hemp. Created in 1951 and composed of 10,000 member companies in 14 countries, the CELC creates an environment which encourages competition between industrial companies in an international context. The CELC works with specialised partners and European professional organisations.

Information: technical@mastersoflinen.com

CELC – LINEN DREAM LAB
15 rue du Louvre
F - 75001 Paris
Tel: +33 (0) 1 42 21 02 35
www.mastersoflinen.com

JEC Group

JEC is an industry organization dedicated to promoting composite materials internationally. It originates from a non-profit association called CPC. The company's policy is to reinvest all income into developing new products and services for its customers and for the composite industry.

JEC supports the development of composite materials by fostering knowledge transfer and exchanges between suppliers and users.

To date, the JEC network connects more than 250,000 professionals from a hundred countries. A strongly user-oriented strategy JEC informs composite professionals about major events, economic, technical and technological developments, new products and applications.

JEC's mission is to organize exchanges and to facilitate connections among all involved players – raw material producers, processors, distributors, machine and software manufacturers, institutions, academics, researchers and users (aeronautics, automotive, marine, land transportation, construction, energy, sports & leisure, EEE, etc).

Six major fields of expertise
Information, Learning, Intelligence, Publications, Innovation, Connecting

International activity
JEC's offer is directed at the 550,000 composite industry professionals around the world, JEC's broad range of products/services and its many promotional activities facilitate the development of business-to-business know-how and connections within the composite industry. Well known for its expertise, the Group is now an acknowledged leader in Europe and worldwide. Its upstream and downstream connections allow JEC to represent the entire industry, from high-tech to consumer products. JEC organizes a "cross-pollination" among the different segments so that all might benefit from the accumulated experience. Many such transfers take place each year at the JEC Composites Shows and Conferences and other meeting platforms of the company.

Headquarters:
JEC Group
25 Boulevard de l'Amiral Bruix
75016 Paris, France
Tel : + 33 1 58 36 15 00
jec@jeccomposites.com
www.jeccomposites.com

Authors: CELC European Scientific Committee

Editorial coordination: Julie Pariset (CELC) and Antoine Morel (JEC Group)

Translator: Carolyn McBride Nafziger

Editors: Frédéric Reux and Ignaas Verpoest

Layout: Marylène Pinault (Atelier du graphiste)

CELC: Frédéric Douchy, President,
Alain Blosseville, Promotion Director,
Benoît Savourat, Technical Section President,
Hubert Brisset, Jan Demeulenaere, Marc Depestele,
Bart Depourcq, Severino Graziano, Raymond Libeert,
Patrick Lonn, Judit Markus, Christian Mekerke,
Elena Salvaneschi, Marek Radwanski,
Xavier Talpe and the representatives of the Technical Section,
Patrick Berghman and Bert Wofcarius,
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CELC's team.

25 Bld de l'Amiral Bruix
75116 Paris - France
www.jeccomposites.com

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