2018 Edition

Flax and Hemp Fiber Composites, a market reality

THE BIOBASED SOLUTIONS FOR THE INDUSTRY

JEC GROUP

CELC EUROPEAN CONFEDERATION OF FLAX AND HEMP

Flax and Hemp Fiber Composites, a market reality

THE BIOBASED SOLUTIONS FOR THE INDUSTRY

As a follow-up to the two preceding editions, we are pleased to put out “Flax & Hemp Fiber Composites, a market reality - The Biobased Solutions for The Industry”

Anne-Carole BARBARIN
Development and Publications Director JEC Group.

The use of composite materials reinforced with renewable plant fibers like flax and hemp is now a reality in a number of industrial sectors, including automotive, aerospace and railway. And many consumer products in the sports & leisure and home design & furnishing sectors are also making use of the technical advantages of flax composites.

The limits for applications and new sectors are constantly being pushed back, and manufacturers are more and more interested in the remarkable properties of these natural fibers.

But what is the state of the art in the European flax & hemp composite industry in 2018? What are the key figures for the industry, the natural fiber trends in the composite market, and the latest news on flax & hemp reinforcements? Who are the players in the value chain, and what strategic vision is there on issues like industrialization, open innovation, competition, or product life-cycle management?

As a follow-up to the two preceding editions (2012 and 2014) of the joint study “Flax and Hemp, a natural solution for the composite industry”, we are pleased to put out a new 2018 version of the work called “FLAX & HEMP FIBER COMPOSITES, A MARKET REALITY – THE BIOBASED SOLUTIONS FOR THE INDUSTRY”, compiled by the European Confederation of Flax and Hemp Confederation - CELC for JEC Group and published by JEC Group.

Besides being a technical update of the two previous editions, this new version offers not only fresh content that zeros in on application markets and on the limits that the industry’s experts and manufacturers are steadily pushing back on things like biosourcing, new industrial-scale reinforcements, characterization and standardization, life-cycle analysis, end of life and recyclability.... but also a new form, rich in applications and finished products, with a focus on value chain participants and things like sourcing, R&D and industrialization partnerships.

This new edition is unquestionably in keeping with the spirit of JEC Group, and with its determination to always push back the limits of what is possible with composites.

In only a decade, the flax and hemp industry has met the challenge of a constantly changing market reality

As renewable European resources, natural flax and hemp fibers have become the champions of a bioeconomy in which their exclusive, reliable mechanical performance properties are more than ever in harmony with sustainable innovation.

In only a decade, the flax and hemp industry has met the challenge of a constantly changing market reality and now proposes a broad range of semi-finished products that demonstrate the technological potential of flax and hemp in the composite industry, in all of its markets and market developments.

Buoyed by the active innovation strategy led by the European flax and hemp industry, these dynamics have successfully met the expectations of all our partners, be they manufacturers, engineering departments, or designers. All sectors are now concerned, including design objects, acoustics, mobility, sports&leisure, automotive, aerospace, interior architecture, wind energy, yachting, and more broadly, consumer goods. All have become our customers.

By establishing its European Scientific Council, the European Confederation of Flax and Hemp [CELC] has been able to lay the foundation for a long-term R&D strategy, helped along by the remarkable properties of flax - of which Europe is the world's leading producer - and guided by an industrialization process in which open innovation plays a prominent role. The industry is fully engaged and ready to meet expectations in the industrial markets.

Flax and hemp fibers have now been proven to fulfill the requirements in expertise, skills, reliability and preform standardization. Their intrinsic environmental performance can also be added to the roster of specifications for a challenging ecological transition.

This work, called Flax & Hemp Fiber Composites, a Market Reality: The Biobased Solution for the Industry, a title that underscores what distinguishes European flax and hemp fibers, is our third co-publication with JEC Group. It proposes a corpus of solutions that are adapted to the new applications and to the societal expectations of the informed consumer.

Marc DEPESTELE
President of the CELC Technical Section.

The CELC and its member companies have managed to anticipate and to harmonize the data

As the leading international intermediary for technical flax and hemp applications in the composite industry, the European Confederation of Flax and Hemp [CELC] created its Technical Section in 2005 and acquired a European Scientific Council of experts from the leading European universities. Together, they reviewed the existing scientific resources and pooled their analytical and characterization techniques to establish the advantages of natural flax and hemp fibers.

To the now proven mechanical performance of these fibers can be added their distinctive qualities, revealing them in their true light as unique biosourced reinforcements to serve innovation and new markets, far beyond their usual scope in traditional textile applications. Not substitute fibers, but ones to create with!

Due to its position at the crossroads of all the expertise, the CELC and its member companies have managed to anticipate and to harmonize the data, identify the growth drivers, pool the benefits of research, and share the information with manufacturers, expert channels and all the participants in the flax and hemp value chain.

The CELC was able to impose the notion of traceability as the basis for its brand EUROPEAN FLAX®, certifying a premium-quality flax fiber in all its markets that is cultivated in Western Europe, the world's leading flax producer.
In so doing, it has created an environment that is favorable to a meeting of the minds with an industry that takes corporate social responsibility seriously, and in the end with a consumer for whom the notions of local production, authenticity and eco-responsibility position flax and hemp as high-performance fibers that are worthy of their trust.

Marie-Emmanuelle BELZUNG
Secretary General of the CELC.

Content

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Editorial on behalf of the CELC European Scientific Council (ESC)

The aim of CELC's European Scientific Council is to bring the science and technology of composite materials and that of flax and hemp fibers together. In this way, the ESC intends to bridge the gap and create fruitful interactions between the industrial world of composite processing/application development and the agricultural world of flax and hemp farming, via the high-tech industry of fiber extraction and processing into advanced flax and hemp fiber preforms.

A careful survey of the scientific literature and technical publications will show that the most advanced research in natural fiber composites has been performed on flax and hemp fibers. Flax and hemp have the longest history in refining and optimizing the fiber extraction process; in addition to that, the flax/linen textile technology is the most advanced of all the natural fibers that are suitable as reinforcement for composites.

With this book, the CELC European Scientific Council intends to present the composite industry with the state of the art in flax and hemp fiber composites. We invite the composite industry to discover all the potential of flax and hemp fibers as reinforcements for composites, and we hope that the book will create a lively interaction between both worlds. Indeed, as for each new material development, the composite industry is curious but also cautious: in real-life applications, will the advantages of the newly presented material live up to the claims?

This book not only presents basic information on flax and hemp fibers, but also provides straight answers to some worries and misconceptions (variability, moisture sensitivity), highlights the newest scientific insights on a range of additional properties (e.g. vibration damping, fatigue, acoustic performance) and scientifically assesses the ecological advantages of using flax and hemp fibers in composites. We will also discuss the most recent preforms developed specifically for composites and highlight a range of fascinating applications.

Of course, not all challenges have been addressed yet, but major steps forward have been made since the first joint CELC-JEC book on flax and hemp fiber composites* was published. By interacting via this new book with the composite community, the flax and hemp fiber community will discover the future requirements for composites, and find creative ways to come up with even better and more efficient solutions for the composite industry.

Ignaas VERPOEST
Coordinator of the European Scientific Council of CELC. Emeritus Professor at KU Leuven, Belgium

* "Flax and Hemp fibers: a natural solution for the composites industry" 2012 with an update in 2014

Belgium

Ignaas VERPOEST

Emeritus Professor at KU Leuven, Belgium.

Professor Dr. Ir. Ignaas Verpoest initiated the research on polymer composites in the Department of Metallurgy and Materials Engineering of the Katholieke Universiteit Leuven in 1982.
As a full professor (from 1991 till 2013), he coordinated the Composite Materials Group, consisting of 10 postdoc and project researchers and 25 PhD-students working in research areas like textile-based and nano-engineered composites, natural fiber 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). As an emeritus-professor, he is still involved in research projects on natural-fiber and carbon-fiber reinforced composites and on hybrid composites. He now serves as Coordinator of the CELC European Scientific Council.

Joris VAN ACKER

Head Professor at the Laboratory of Wood Technology of the Ghent University.

Joris Van Acker has been Professor at the University of Ghent and head of the research group in the Laboratory of Wood Technology (Woodlab) since 2005. In addition to wood-related research, his team works on topics that cover similar features for natural fibers. For structural and anatomical analysis, CT scanning at micro and nanoscale is performed at the interfaculty Center for X-ray Tomography (UGCT). Research related to natural fibers focuses on moisture dynamics and both abiotic and biotic degradation. Formerly the president of InnovaWood (European federation of wood research institutes), he currently is president of the International Research Group on Wood Protection, and has co-authored over 100 publications in refereed journals.

Kevin HENDRICKX

PhD researcher at the department of materials engineering at KU Leuven.

Kevin Hendrickx is a PhD researcher in the Department of Materials Engineering at KU Leuven. He currently studies the influence of humidity on the mechanical behavior of flax-fiber composites. His other expertise includes fiber and composite processing as well as fiber treatments.

Denmark

Hans LILHOLT

Emeritus Scientist Composites and Materials Mechanics Section, Wind Energy Institute, Risø Campus Technical University of Denmark, Roskilde.

Hans Lilholt is an emeritus scientist within the Composites and Materials Mechanics Section of the Wind Energy Institute at the Risø Campus of Technical University of Denmark. His research areas include metal-and polymer-based composite materials reinforced with inorganic, organic and natural fibers; 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 fibers and biopolymers.

France

Christophe BALEY

Professor at the University of Bretagne Sud, IRDL (Institut de Recherche Dupuy de Lôme).

Christophe Baley is a professor at the University of Bretagne Sud, IRDL (Institut de Recherche Dupuy de Lôme) in Lorient, France.
Since 1991, he has been working on natural fiber reinforced composites, specifically those with an organic matrix. He studies the mechanisms of plant fiber reinforcement.

Moussa GOMINA

Research Scientist, CRISMAT laboratory, CNRS at ENSICAEN.

Moussa Gomina is research scientist for the CNRS Crismat Laboratory at the national school of engineering ENSICAEN in France. His work focuses on the relationship between microstructure and the mechanical behavior of ceramic materials developed for transport properties and of synthetic fiber or plant fiber reinforced structural composites. The durability of the composites is analyzed in terms of the influence of temperature and humidity on the damage and fracture mechanisms.

Peter DAVIES

Researcher at IFREMER, the French Ocean Research Institute, Brest.

Peter Davies is a researcher at IFREMER, the French Ocean Research Institute in Brest.
He has been working there for over 20 years on the durability of polymers and composites in a marine environment.

Germany

Jörg MÜSSIG

Professor at Hochschule Bremen – HSB, City University of Applied Sciences, Bremen.

Jörg Müssig has been a professor in Biological Materials at the Hochschule Bremen - University of Applied Sciences in Bremen, Germany since 2007. 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. – FIBER – where he was the leader of the Bio-based Materials/Sustainability department from 2001 to 2007. From 2004 to 2009, he was an appointed member of The Young Academy in Berlin, Germany. His current research topics include the development of concepts for sustainable materials, bio-inspired materials, natural fibers & natural fiber composites, and adhesion & interphases.

Gerhard ZIEGMANN

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

Professor Dr. Ir Gerhard Ziegmann works within the Institute for Polymer Materials and Plastics Processing at Clausthal University of Technology in Germany, on natural and man-made fiber composites and the surface modification and processing of composites.

Mission of the CELC European Scientific Council

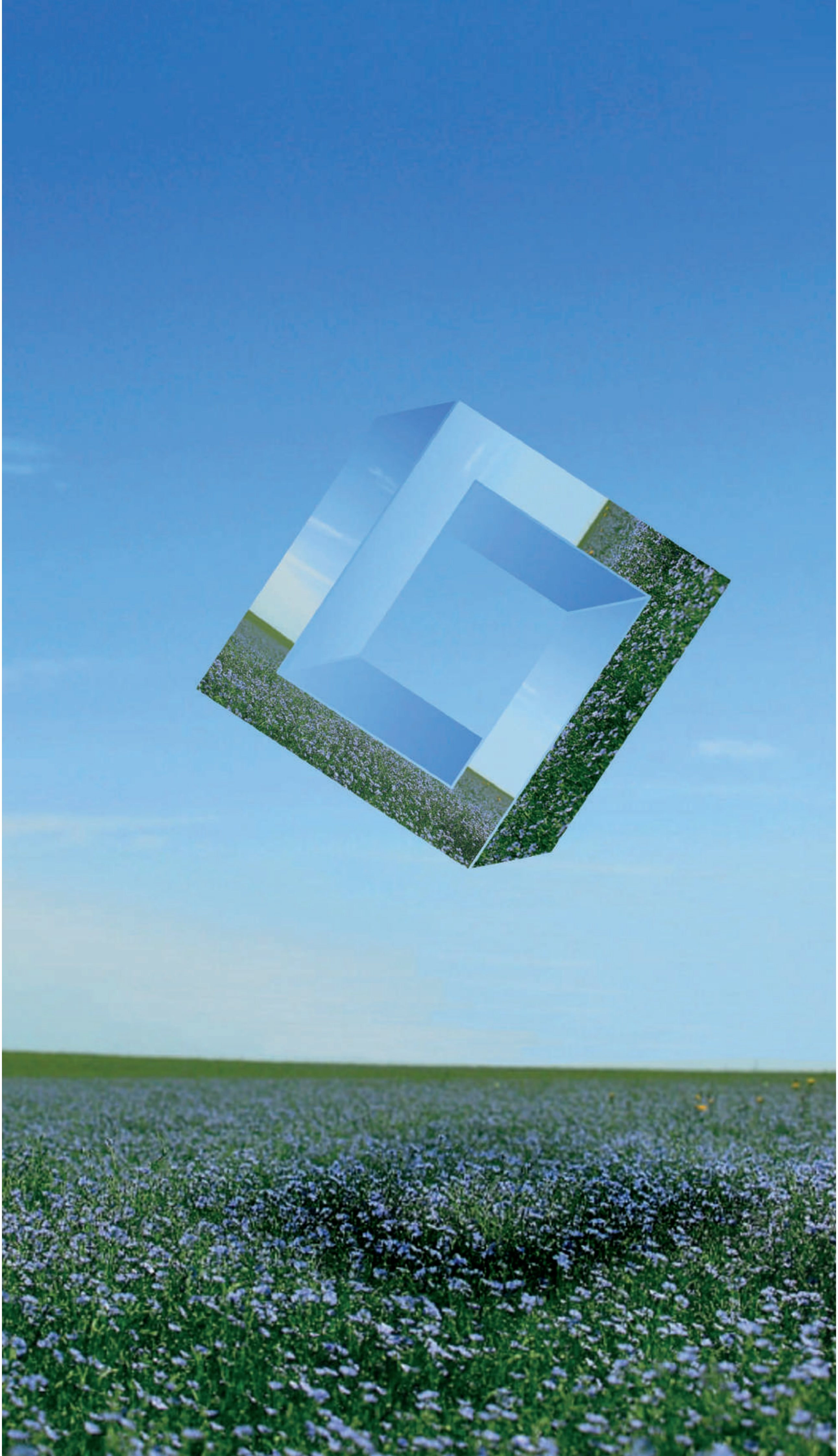
The mission of the European Scientific Council is to support CELC activities undertaken to improve the market position of flax & hemp preforms. This is being through the following actions:

- Networking within the flax & hemp research community to encourage and organize interactions between research institutes working on flax & hemp composites. A database on research projects and technical publications on flax & hemp fiber composites is available at **www.europeanflax.com**
- Communicating and sharing with composite manufacturers through the organization of technical conferences and the publication of technical books and papers on flax and hemp fiber composites.
- Providing support to the flax and hemp value chain in the form of standardized technical datasheet templates for flax and hemp fibers and preforms, along with guidance for their use and assistance in characterizing products in a way that is relevant for the composite industry.
- Promoting research on relevant topics in correlation with the industry's strategy.

Julie PARISET

Publication Coordinator and Operation Manager at CELC.

She has managed the Technical Section of the European Confederation of Flax & Hemp since 2009. This Section uses an open innovation approach to help ensure that the industrialization capabilities of the flax and hemp value chain correspond to the needs of the multi-sector industry, e.g. for high-performance composites. On behalf of the European Scientific council, she harmonizes the basic and applied research skills that are specific to flax and hemp fibers.



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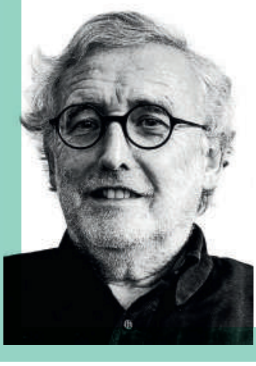
What Is the Current Status of Flax and Hemp Fiber Composites?



Ignaas VERPOEST

Emeritus Professor at KU Leuven, Belgium.

The secret of composites

Composite materials combine the advantages of their components: the stiffness and strength of the reinforcing fibers and the lightness and ease of manufacturing of the polymer (or “plastic”) matrix.

The difference in their mechanical properties is huge, as shown in Figure 1: at 0% fiber volume fracture (V_f), the stiffness of the polymer matrix is represented, typically varying from 1 GPa for polypropylene (PP) to 3 GPa for epoxies and polyesters. The stiffness of the fibers, however (see on the right side, at 100% fiber volume fraction), varies from 70 GPa for glass fibers to 230 GPa for standard carbon fibers, or 20 to almost 100 times higher! The lines in between 0 and 100% represent the stiffness of a composite reinforced with fibers that are all parallel to each other (unidirectional), and measured in the direction of these fibers (longitudinal).

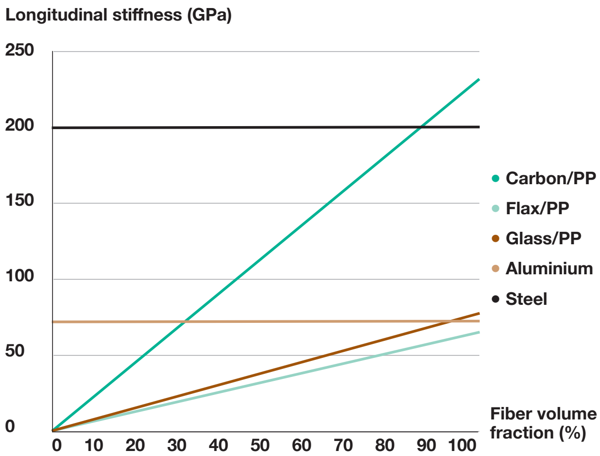


FIG. 1 **Simple linear rule-of-mixture for the longitudinal stiffness E of a composite, reinforced with unidirectional fibers. Values for steel and aluminum are added as horizontal lines for reference.**

The difference with other structural materials like steel or carbon is represented by the horizontal lines for steel (stiffness = 200 GPa) and aluminum (70 GPa).

However, steel and aluminum are heavy materials compared to composites, with a density of 7.8 and 2.7 kg/dm³, compared to 1.4 and 1.8 kg/dm³ for carbon or glass fiber composites, respectively (at typically V_f =50%).

For many applications, the weight of the structure or product is very important. This is certainly the case for all products that move, like cars, airplanes or bicycles, because the amount of energy required for the movement is heavily dependent on the mass of the car, airplane or bicycle. However, weight reduction is important for many non-moving applications (e.g. self-supporting bridges or large buildings). And, if we can reduce the weight of a product, we also reduce its environmental impact, since less material has to be produced (and recycled).

Therefore, the mechanical properties are often represented as "specific stiffness" or "specific strength", meaning the stiffness or strength divided by the density. It has been shown (and will be further explained in **Chapter 2** of this book) that these specific mechanical properties are the most important parameters in the quest for lightweight designs and products. In Figure 2, the specific stiffness in bending (see **Chapter 2** for further explanation) is presented. It is striking that carbon fiber composites (UD fibers, longitudinal), from V^f =3% on, always perform better than steel or aluminum in stiffness-critical bending applications. Even unidirectional glass fiber composites perform better, but most surprising is that unidirectional flax fiber composites outperform steel, aluminum and glass fiber composites.

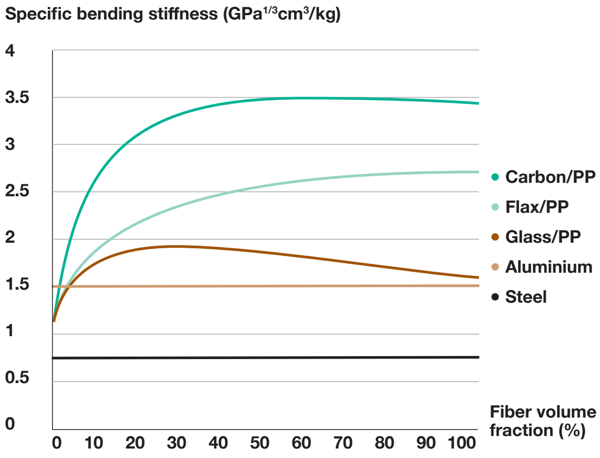


FIG. 2 **Specific longitudinal stiffness in bending of a composite, reinforced with unidirectional fibers.**

The excellent specific mechanical properties of natural fibre composites motivates composite scientists and engineers to investigate their potential. As will be explained in Chapter 2, flax and hemp fibers are among the strongest and stiffest natural (or bio-based) fibers, with typical stiffness values of 65 and 45 GPa, respectively. This book will offer extensive information on the properties of flax and hemp fiber composites, and explain how their composites can be processed and which products and applications have been developed recently.

The composite market: trends

In the following, the meaning of "composite materials" will be restricted to "fiber reinforced polymers", to the exclusion of particle-filled plastics, or fiber reinforced metals or ceramics.

The market for composite materials and their applications is still considered to be an "emerging" one. Although glass fibers were introduced in the industry just before World War II, it has been only since the invention of carbon fibers in the late 1950s and their commercial introduction in the 1970s that the potential of fiber reinforced polymers has been fully exploited. Due to their high specific mechanical properties, mentioned earlier, composite materials have been gradually optimized, fiber preforms have been developed (see **Chapter 3**), and manufacturing processes have been invented and/or adapted see **Chapter 7**). Mainly due to the latter being rather different from manufacturing with traditional structural materials such as steel or aluminum, the development of the market for composites was initially slow. However, its growth has picked up considerably over the past 20 years and continues to speed up.

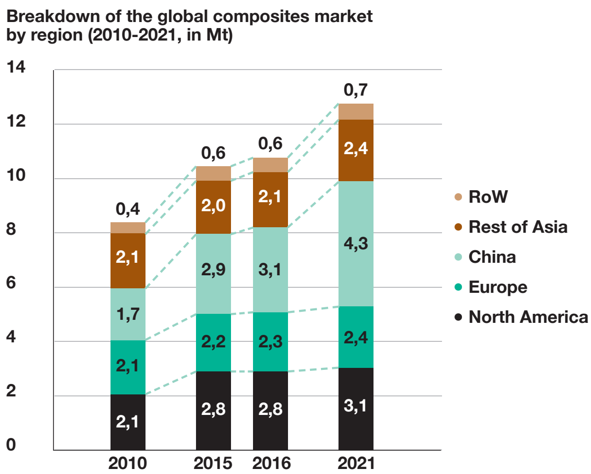


FIG. 3 **Breakdown of the global composite market by region, expressed in megatons** (Source: Overview of the global composites market, JEC, 2017).

In 2016, the total worldwide market volume for composite materials was 10.8 Mt (or ~11 million tonnes), and the growth rate (CAGR, compound annual growth rate) was 4% per year over the period 2010-2016, much larger than for any other family of structural materials (Overview of the global composites market, published by JEC- Group, 2017; all market-related data and figures in this paragraph are cited from this book). The growth is slow in Europe, steady in North America and strong in China, with growth figures for the 2010-2021 period of 15, 48 and 147%, respectively.
The growth potential of China is large, because on a per capita basis, China produces only 2 kg/inhabitant, whereas the USA produces about 8 kg/inhabitant, and European countries like Germany, Spain or The Netherlands, about 6 kg/inhabitant (see Figure 4). If China were to achieve the same gross domestic product (GDP) as European countries, its actual production of composites would probably triple.

Composites volume per capita (2016, in kg per inhabitant)

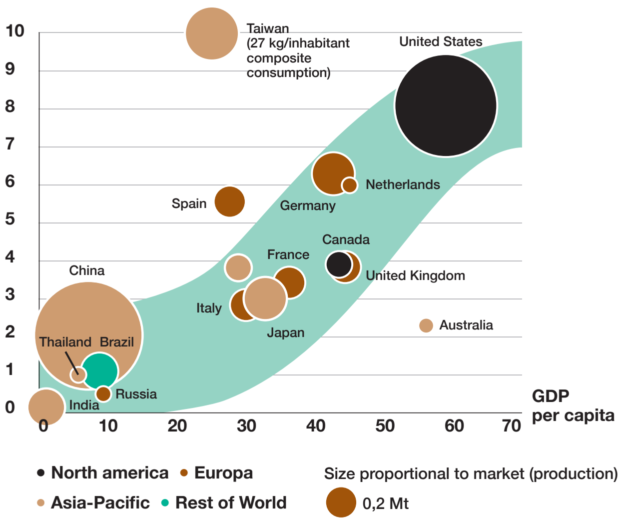


FIG. 4 **Volume of composites per capita in 2016, expressed in kg per inhabitant, as a function of the GDP per capita in the specific country** (Source: Overview of the global composites market, JEC, 2017).

The idea that composites are used mainly in the aerospace industry is a gross misunderstanding! Figure 5 shows that, expressed in billions of US$, transportation is and will remain (worldwide) the largest market for composite materials, followed by construction and aerospace. These application areas are also expected to contribute the most to the overall growth of the composite industry for the 2016-2021 period, accounting for 20% (transportation), 13% (construction), and 16% (aerospace) of total expected growth.

Breakdown of the global composites market by application area (2010-2021, in Bn$)

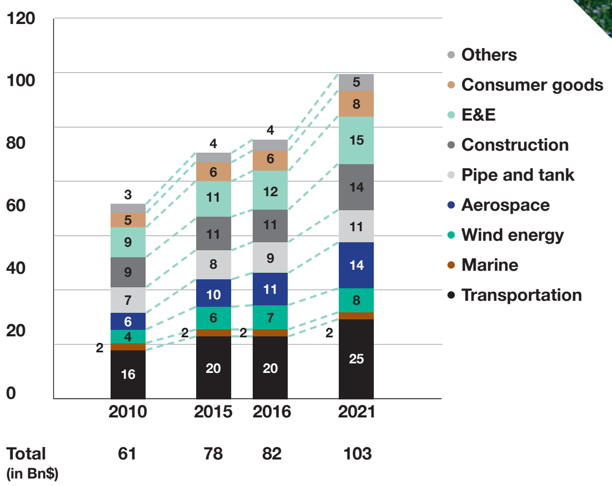


FIG. 5 **Breakdown of the global composite market by application area, expressed in US$ billion** (Source: Overview of the global composites market, JEC, 2017).

It is interesting, however, to note that growth expectations are quite different for different application areas in different regions. In Europe, the largest growth is expected in the transportation area; in North America, in aerospace and in China, in wind energy (see tables 5 to 7, pages 105-107 in the JEC book Overview of the global composites market, 2017).

Finally, over the period of six years from 2009 to 2015, a change in the use of different fibers and matrices was observed: as the total market value for reinforcement fibers grew from 7 to 9.3 billion US$, the share of carbon fibers increased from 17 to 23% at the expense of glass fibers. For matrices, the share of thermoplastics increased more gradually from 34% in 2009 to 38% in 2016, at the expense of thermosets.

The market position of natural fiber composites

The market position of natural/biobased fibers in composites is not well documented. Reliable statistics highlighting the use of natural fibers as reinforcement for composites are hard to find, partially because data on flax, hemp and other (plant) fibers are often embedded in statistics which also comprise data on wood polymer composites (WPC).

WPC (wood plastic composites)	**260,000**
Decking	174,000
Automotive	60,000
Siding and fencing	5,000
Furniture	2,500
Consumer goods	2,500
NFC (natural fiber composites)	**92,000**
Automotive	90,000
Others	2,000
Total WPC + NFC	**352,000**
Total composite production in European Union	2.4 million tonnes
(glass, carbon, WPC and NFC)	90,000
% of WPC and NFC	*15%*

TABLE 1 **Market volumes of biobased composites (WPC and NFC) in Europe in 2012, in different application areas.**

A recently published study that was compiled by the Nova Institute "Verbundwerkstoffe" and edited by FNR, Fachagentur Nachwachsende Rohstoffe, 2017 (in German) presents fairly detailed data for both natural fiber composites (NFC) and wood polymer composites (WPC), although the data apply only for the year 2012: lumped together, the two types of composites represented 15% of the total European market, with WPC accounting for two-thirds, or 260,000 tonnes, of that. WPC were used mainly in extruded deckings and façade elements (sidings, fencings) which, lumped together, accounted for 73% (or 190,000 tonnes) of all WPC.
The remaining one-third (92,000 tonnes) consisted of composites reinforced with other types of natural fibers (NFC).
In 2012, the largest application area for NFC (90,000 out of the 92,000 tonnes) was the automotive sector. (Note: of these 90,000 tonnes, recycled cotton fiber reinforced thermoset composites accounted for 30,000 tonnes and (mainly) flax and hemp fiber composites, for the remaining 60,000 tonnes. They are used both in typical long-fiber composite processes (compression molding, RTM, etc.) and in short-fiber based injection molding and extrusion processes.

The NOVA Institute updated these figures in a recent press release (November 16 2017), presenting data for 2017, albeit without making the distinction between NFC and WPC. The volume of applications in deckings, sidings and fencings (typically extruded WPC) has shown only very limited growth, whereas automotive applications seem to have stalled (150,000 tonnes, of which 60,000 tonnes WPC and 90,000 tonnes NFC).
The surprising fact is the strong growth in other application areas (technical, furniture, consumer goods) from 17,000 to 60,000 tonnes, or an annual growth of almost 30%. Just how much of this growth is realized by NFC is not clear at this moment. From another study by the NOVA Institut (Natural fiber reinforced plastics: establishment and growth in niche markets, December 2017), however, it can be deduced that strong diversification is occurring: not only PP but also PLA, PE and other polymers are used, with natural fibers being used in many more applications – and therefore certainly taking up a larger percentage of the total WPC+NFC market. More precise data is not available to date.

Biobased composites *(nfc, wpc and others)*	**Main production method**	**2012** *Tonnes*	**2017** *Tonnes*	**CAGR in %**
Decking, siding and fencing	extrusion	190,000	200,000	1
Automotive	compression molding	150,000	150,000	0
Technical application, furniture and consumer goods	injection molding compression, molding, RTM, 3D	17,000	60,000	29
Total		**357,000**	**410,000**	**3**

TABLE 2 **Increase in market volumes of biobased composites (WPC and NFC) in Europe from 2012 to 2017, in different application areas.**

As will be explained in the "applications" chapter of this book (**Chapter 7**), natural fiber composites are entering many different application areas. The automotive sector, however, is one of the leading sectors, and the only one for which quantitative market data seems to be available. In the same Nova study, an analysis was made of the use of natural fibers in automotive applications in Europe,where in 2012, a total volume of 80,000 tonnes of various wood and natural fibers were used in 150,000 tonnes of composites in passenger cars and trucks, for an average weight fraction of 53% in such composites. WPC account for 38%of these composites, followed by cotton (25%) and flax (19%) fiber composites. Concentrating on the non-wood and non-wool natural fibers (Figure 6), in 2012 flax fibers accounted for more than half (51%) of those used, or about 15,000 tonnes in absolute terms. Data for 2017 are not yet available. Together with hemp fibers (3,800 tonnes), these leading European natural fibers cover two-third of all natural fiber composites in the European automotive market.

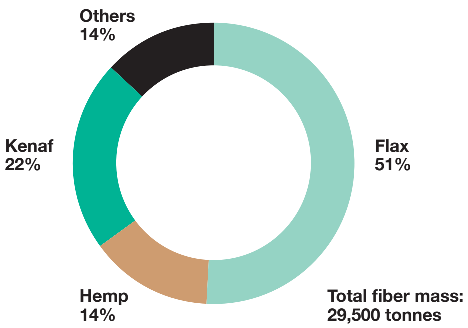


FIG. 6 **Use of natural fibers, excluding wood and cotton, in European automotive applications (2012)**

Presenting the main characteristics of the flax and hemp fiber production /value chain

As will be explained in **Chapter 2**, flax and hemp fibers have excellent mechanical properties compared to other natural fibers like jute, ramie and kenaf. Flax has a stiffness that is similar to glass fibers, but when one takes into account the fact that the density of natural fibers is only 60% of that of glass fibers, it is clear that there is a great potential to replace glass fibers in many structural and semi-structural applications (see **Chapter 2** for data on "specific" fiber properties, taking into account the density of the fibers).

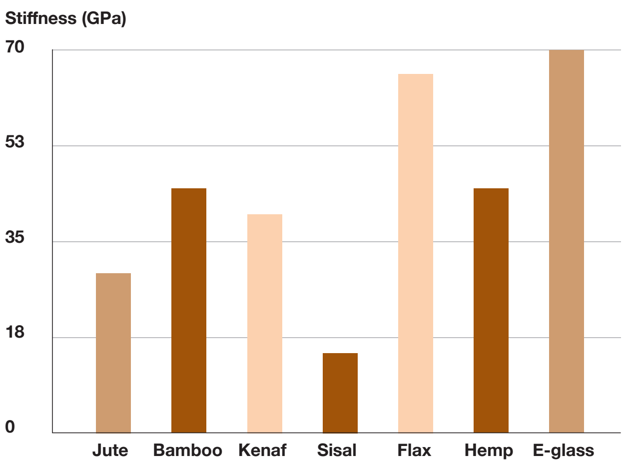


FIG. 7 **Typical stiffness values for natural fibers, compared to glass fibers.**

The increased market penetration of flax and hemp fiber composites is directly related to these excellent mechanical properties, but also to the research and development efforts of many academic, governmental and industrial research groups to further improve the efficiency of using flax and hemp fibers as reinforcements for composites. In **Chapter 6**, several "added values" of flax and hemp fiber composites

What's in a name: natural, biobased, biosourced, vegetable, or renewable fibers?

There is quite some confusion about the correct terminology when flax and hemp fibers have to be positioned vis-à-vis synthetic fibers like carbon and glass fibers.

- **"Natural fibers"** *seems to be the most common name for flax, hemp, kenaf, ramie, etc., but how to define "natural"? Is white sand on the beach, from which the "synthetic" glass fibers are made, less natural than the fibers from a hemp plant, growing on the field?*
- **"Renewable"** *then seems to be a more appropriate term, because it can distinguish between sources which we extract (and exhaust) from the earth, like sand for glass fibers or petroleum for carbon fibers, and renewable resources, which we can re-grow yearly (flax, hemp…) or every so many years/decades (wood fibers from trees). But this term is not unambiguous, either, if only because the period over which the fibers can be "renewed" can be very different, as indicated.*
- **"Vegetable"** *fibers, a term often used in France, is perhaps too limiting, because it deals only with (cellulosic) fibers extracted from plants, so it excludes wool or silk fibers, for instance. (Also, for the non-French speaking part of the world, "vegetable" refers intuitively to vegetables that we eat, like salad, beans and carrots.)*
- *The most neutral term seems to be* **"biobased"** *or* **"biosourced"** *fibers. The use of the term* **biobased** *is advocated in the preamble to the excellent study Integrate bio-based products in your composites by IAR, the French Bio-Economy Cluster, 2017. They point out that many materials are not fully biobased, like some epoxy resins that might contain only 60% of biobased chemicals. Fortunately, for fibers the situation is more straightforward, as a fiber cannot really have a mixed "bio/synthetic" source (unless the treatment would be such that, for instance, a lot of non-biobased chemicals had to be used during the extraction and refining process of the fibers).*

Therefore, we propose to use the term "biobased" throughout the text, *with "natural" as a second best.*

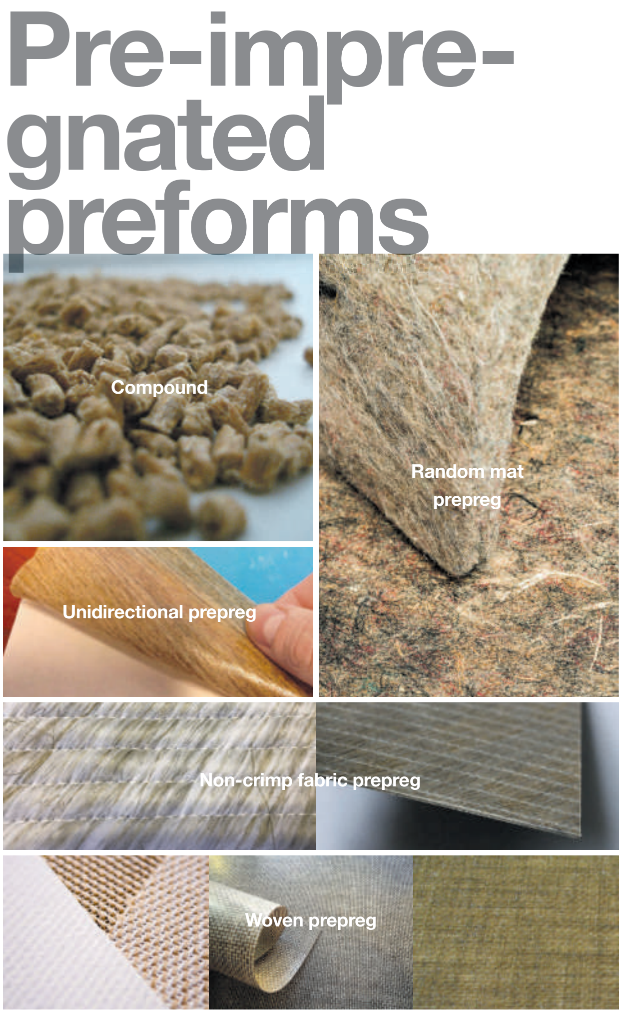
In the IAR-study, reference is made to methods for measuring the 'biobased content" of a material. Several European standards are now available to determine the biobased content, developed in the framework of the technical committee CEN/TC411 "Biobased products". Similarly, the American standard ASTM D6866 determines how to measure the biobased carbon content of a material. Further details and references can be found in the IAR study.

will be highlighted, such as the good fatigue and impact performance, or the excellent vibrational damping that has led to the development of hybrid composites. In these hybrids, carbon and flax fibers are combined in order to take advantage of the high stiffness of carbon and the high damping of flax fibers.

Similarly, the acoustic (damping) properties are being exploited in several applications. Recent research has also resulted in guidelines on how to control and improve their behavior in humid environments. Moreover, flax and hemp fiber composites can be made biodegradable, which for certain applications is another important "added value".

FIG. 8 **Overview of the different preforms on the market for flax and hemp fibers.**

All these R&D-based innovations can only become relevant for the composite industry if the fibers are available in shapes and forms that the composite industry is used to. The major innovation of the last five years is therefore, without any doubt, the development of a large variety of fiber preforms, as shown in Figure 8. All these preforms will be extensively described in **Chapter 3**, whereas in **Chapter 7**, the different composite processing techniques that use such preforms will be introduced, along with the presentation of a large number of new applications. A global overview is presented in Figure 9.
With such excellent mechanical properties and well-developed preform technologies, it is no surprise that flax and hemp fibers together constitute about 2/3 of all natural fibers used in composites for automotive applications,



as was shown in Figure 6. This expands now to other application areas (see also **Chapter 7** and Figure 9 above), where the trend is clearly upwards: according to the data in Table 2, the use of NFC and WPC in technical, furniture and consumer goods applications has increased by a factor of 3.5 (from 17,000 to 60,000 tonnes between 2012 and 2017). As has been mentioned earlier, qualitative data collected by NOVA indicates that the share of NFC, and so certainly of flax and hemp fibers, has strongly increased as well.

FIG. 9 **Market reality in multiple application areas.**

There is no doubt that the flax and hemp industry can cope with this increased demand. The value chain, from flax and hemp farmers via fiber extraction and refining companies up to producers of rovings and yarns, is very well integrated. In Europe, where the vast majority of flax and hemp fibers are produced, the actors in this value chain are grouped in the **CELC, the European Confederation of Flax and Hemp**.
It is the only European agro-industrial organization to unite all the stages of production and transformation of flax and hemp. Founded in 1951, it is the privileged intermediary for 10,000 European enterprises across 14 countries, overseeing fiber development from plant to finished product.

Since 2005, the Technical Section within CELC provides support to develop specific products for the composite industry via a wide variety of activities, including:

- organization of a European skills network that includes companies, universities and research centers,
- harmonization of the basic and applied research skills that are specific to flax and hemp fibers,
- positioning of flax & hemp as natural, renewable and technical fibers, innovative and performing, on a multi-sectorial approach.

With its European Scientific Council, CELC helps its members move towards the future to discover new opportunities, such as high-performance composite products. Operational advice from experts provides the value chain with support in:

- Standardization
- Training
- Publication of reference works
- Information sharing

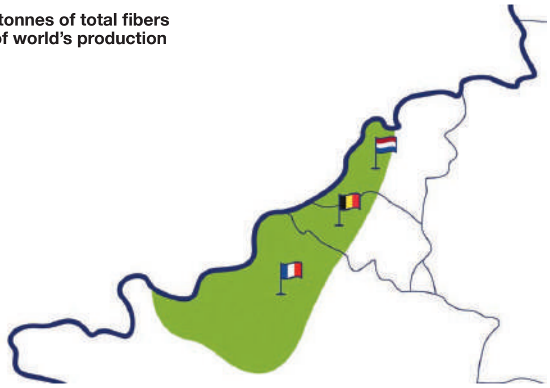


FIG. 10 **European production of flax fibers** (dm and cm).
Source: Harvest figures - 2017 Campaign, CELC Cultivation-Scutching

The production of flax fibers dm and cm is concentrated in three countries: France, Belgium and the Netherlands and represents 209,000 tonnes or 76% of the worldwide production. (Figure 10). The above numbers do not take the production of linseed flax for oil into consideration.

Flax/Linen is a multi-use fiber for numerous and innovative applications: fashion textile, 60%; lifestyle textile, 30%; and technical products including composite, 10%.

In 2016, The European production of **hemp** fibers was about 25,000 tonnes. The main application is in high quality paper, for 57%. Insulation accounts for 26%, and the use in biocomposites, for 14%.

The supply of both flax and hemp fibers is secure, and the production chain is well organized. The 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 fiber producers as partners
- Buffer stocks: safety inventories to guarantee a reliable supply in terms of available volumes and fiber quality
- Multi-supplier resources: increasing the number of fiber supply outlets cuts down on dependence and lowers risk, and can even push suppliers to compete.

In conclusion, it can be stated that the flax and hemp fiber industry offers a **dynamic and reliable production/value chain**. Of all natural fibers used as a reinforcement for composites, flax and hemp have the longest history in developing high performance products. The flax and hemp industry is well organized, both nationally and internationally, and offers a strong service to the composite industry. In past years, technical datasheets were developed (see **Chapter 4**) to encourage the flax and hemp fiber producers to present their fibers in the same way the composite industry is used to seeing for glass and carbon fibers. In doing so, it is expected that the market acceptance of flax and hemp fibers will be strongly supported. Along the same lines, a method for measuring the fiber properties, which is already well accepted for glass and carbon fibers, has been adapted for flax and hemp fibers (see also **Chapter 4**). This Impregnated Fiber Bundle Test (IFBT) is now actively being introduced to the lax and hemp fiber producers and preform manufacturers.

The use of both the technical datasheets and the Impregnated Fiber Bundle Test (IFBT) will help to counteract an often voiced concern, namely that natural fibers in general would vary significantly in their (mechanical) properties. Measuring and presenting these properties correctly and reliably would already help in easing this concern, but in **Chapter 5**, more fundamental and scientific arguments are presented to counteract these prejudices.

Finally, the most obvious argument for using flax and hemp fibers as reinforcement in composites is evidently the fact that they offer a strong answer to societal and environmental challenges:

- the use of renewable material resources;
- environment friendly: the EUROPEAN FLAX® Charter, signed by all the Flax producers, guarantees local farming that respects the environment: zero irrigation, gmo-free, zero waste;

European Flax® Premium linen fibre

EUROPEAN FLAX® is the qualitative standard of European Flax fiber for all uses (fashion, lifestyle, home and composites), promoting origin, know-how and innovation. Audited by Bureau Veritas Certification, it certifies traceability at each step of the processing, right through to the finished product, and provides reassurance to a demanding industry user and consumer.

- the potential of CO_2-storage: every year, the growing of flax in Europe results in the capture of 250,000 tons of CO_2, equivalent to the CO_2 emissions generated by a Renault Clio car driving around the world 62,000 times (Source: The Barometer of European Flax/Linen 2015, a CELC Report by BVA and BIO BY DELOITTE - CELC);
- energy saving: taking the energy needed for producing one kg of fibers as a comparative parameter, flax requires under 10 MJ/kg, or 5 times less than glass fiber, and 25 times less than carbon fiber.

The societal and environmental advantages of flax and hemp fiber composites will be extensively discussed in **Chapter 8**.

IN SUMMARY: THE MAIN TRENDS IN FLAX AND HEMP FIBER COMPOSITES

- **Innovative and improved reinforcement architectures, new preform solutions on the market**
- **Hybrid preforms are emerging, combining unexpected performance with aesthetics**
- **Reliable data are provided with help of the technical datasheets**
- **CELC is the established European organization for the production of flax & hemp fibers, and guarantees an organized value chain to meet the demand**
- **The excellent mechanical properties are now supplemented with “remarkable” properties like vibration damping, fatigue resistance, acoustic erformance, and more.**

II

Why Use Flax and Hemp Fibers to Reinforce Composites ?

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Cellulose fibers and their competitors

The fibers originating from the flax and hemp plants are based on cellulose, hemicellulose and lignin. Because cellulose accounts for the largest fraction, the fiber properties and behavior are governed by those of cellulose. The flax and hemp plants are different botanical varieties. They are grown on different soils, and are subject to different growth and climate conditions from year to year, so the properties are aptly to vary. The range of observed property values has usually been fairly wide, although flax and hemp producers are now able to deliver fibers with more reliable and constant properties, as will be described in Chapter 6. This enables us to use typical values for flax fibers and for hemp fibers. The 2012 edition of this book dealt with the details of these fibers, with the mechanical properties being described in Chapter 7.
In this edition we will benchmark the performance of flax and hemp fibers against other fibers (glass, carbon/graphite, aramid and polyethylene), in particular their performance under mechanical loads. All of these fibers are used as reinforcement within polymer matrices to form composites. Because glass fibers and carbon fibers are in more widespread use, we will use them for the benchmarking. The 2012 edition explained the mechanisms of fiber reinforcement and the composite performances. Here, we will discuss some of the composite properties used for the benchmarking.

Form of fibers and their semi-finished-products

All the fibers are generally available in various forms that allow the fibers to be integrated with the matrix during the composite fabrication process. The forms are typically fiber bundles (tows, rovings) to ensure unidirectional fiber alignment, and various types of woven fabrics to allow fibers to be configured in several directions, typically two and sometimes three or four directions. These choices of directions are closely linked to the resulting properties of the composite. The fibers and some of these different fabrics are shown in the figures 1 to 5.

FIG. 1 **Flax fibers: spool and group of individual fibers**

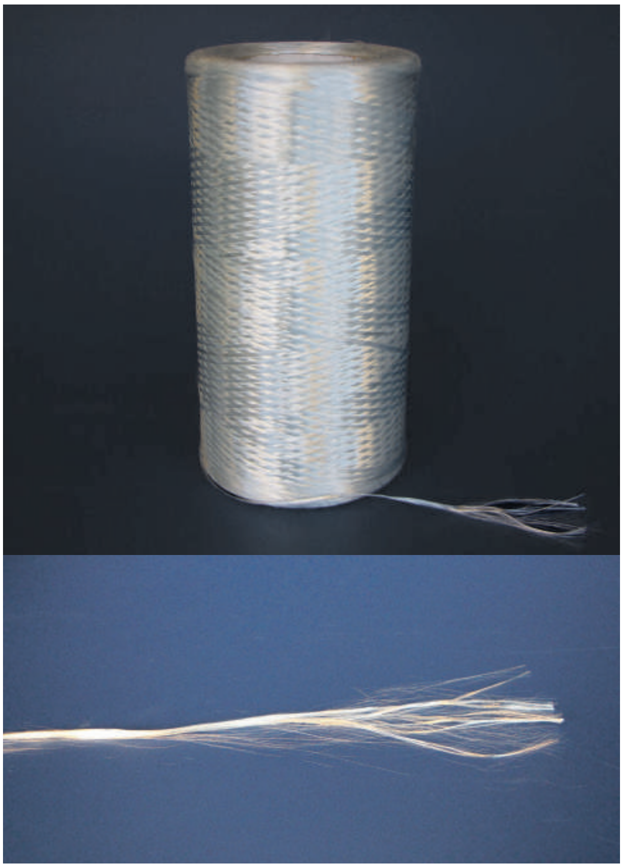


FIG. 2 **Glass fibers: spool and group of individual fibers**

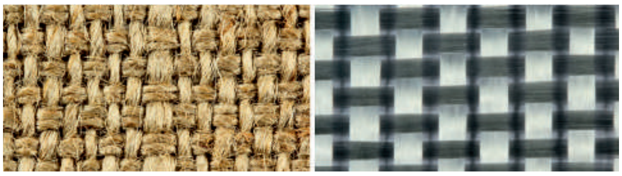


FIG. 3 **Balanced woven fabric of fibers, orientations 0° and 90°, (a) flax, (b) glass**

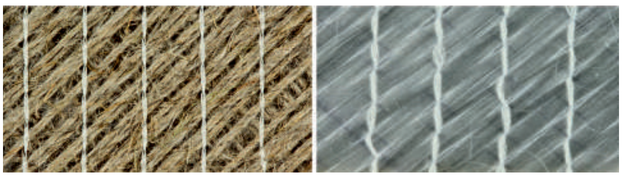


FIG. 4 **Balanced non-crimp fabric of fibers, orientations +45° and -45°, (a) flax, (b) glass**

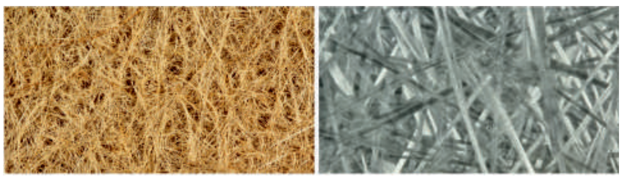
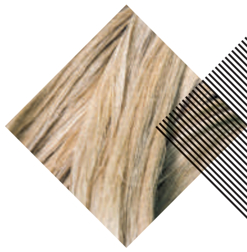


FIG. 5 **Random mat of fibers, uniform distribution of all orientations, (a) flax, (b) glass**



Fiber properties

The properties selected here to give a general overview and to show typical values are: density, stiffness and strength. Other properties such as moisture uptake, vibrational damping capacity and energy content based on LCA analyses will be described in Chapters 5 and 6. The properties of the fibers are used to derive (calculate) typical properties and thus performance values for the composites.

Fiber characteristics

FIBER	HEMP	FLAX	GLASS	CARBON
Density, g/cm³	1.5	1.5	2.6	1.8
Stiffness, GPa	45	65	70	230
Strength, MPa	600	800	2000	4000

The density values are relatively well defined. The stiffness values are typical for the fibers, with a range of 50-70 GPa for flax fibers, and about 30-60 GPa for hemp fibers.
The strength values are typical, with a broad range for all fibers.

HISTORY

Hemp fibers have been used for centuries, especially in ships, for the rigging to support the masts and for sheets and halyards for controlling the sails. The Royal Navy in England was established in the 1660-s. The Navy Board was in control of the administration of the Navy, and the clerk of the acts (secretary) was Samuel Pepys (1633-1703). He kept a detailed diary during the years 1660-1669, and recorded both private and national daily life. On 2 March 1663 he wrote:

"*and then to the Ropeyard, and saw a trial between Riga hemp and a sort of Indian grass, which is pretty strong, but no comparison between it and the other for strength, and it is doubtful whether it will take tar or no.*"

Composite parameters

Only in the form of composites can the fibers function as materials for applications such as load bearing. The fibers must be incorporated into a matrix, that binds the fibers together so that the (very many) individual fibers work together. For any given polymer matrix the density of the composite depends only on the amount of fibers (volume fraction or mass fraction), while the stiffness and the strength depend on the fiber fraction and the orientation of the fibers relative to the loading direction. The table lists typical matrix properties for a polymer used in composite. The table also gives the approximate orientation factors for typical fiber orientation arrangements, corresponding to the typical fiber fabrics illustrated above.

POLYMER MATRIX and FIBER ORIENTATION FACTORS

	POLYMER MATRIX	FIBER ORIENTATION FACTOR
Density, g/cm³	1.2	
Stiffness, GPa	3	
Strength, MPa	50	
Woven, 0°/90°		0.50
Non-crimp, +/-45°		0.25
Random		0.375

Composite properties

The composite properties are calculated from the equations given in the 2012 edition. The relevant equations are shown in the box, where V is the volume fraction, and the indices c, f and m indicate composite, fiber and matrix, respectively.

In the equation for strength the σ^*_m is the matrix stress at the failure strain of the composite. For the stiffness and strength of fabric based composites the orientation factor must be included. This is done by multiplying the orientation factor onto the fiber stiffness and the fiber strength, respectively. Each property is given in a table for all four composites, which are listed in the same order in all tables. Data are shown for typical composites with a relatively low fiber fraction of 30%, and a relatively high fiber fraction of 50%.

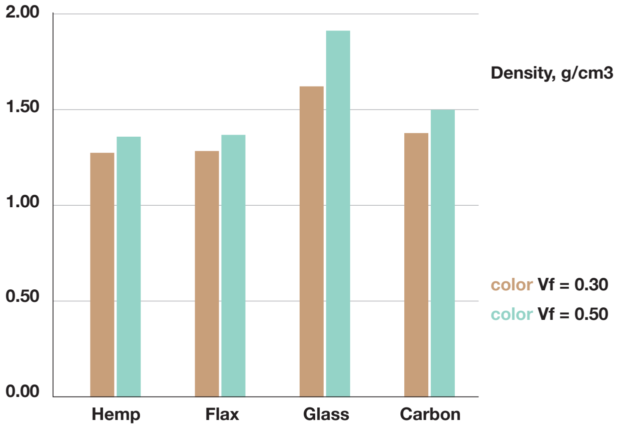
Density: $$\rho_c = V_f \cdot \rho_f + V_m \cdot \rho_m$$

Stiffness: $$E_c = V_f \cdot E_f + V_m \cdot E_m$$

Strength: $$\sigma_c = V_f \cdot \sigma_f + V_m \cdot \sigma^*_m$$

Density for composites

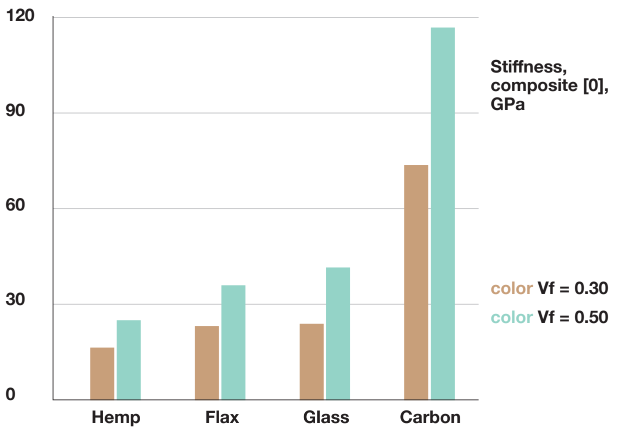
DENSITY, g/cm³	COMPOSITE, V_f =30%	COMPOSITE, V_f =50%
Hemp	1.29	1.35
Flax	1.29	1.35
Glass	1.62	1.90
Carbon	1.38	1.50



The density values for composites densities are all low, with flax and hemp fiber composites ranked with the lowest values. The densities increase with fiber volume fraction.

Stiffness for aligned fiber composites

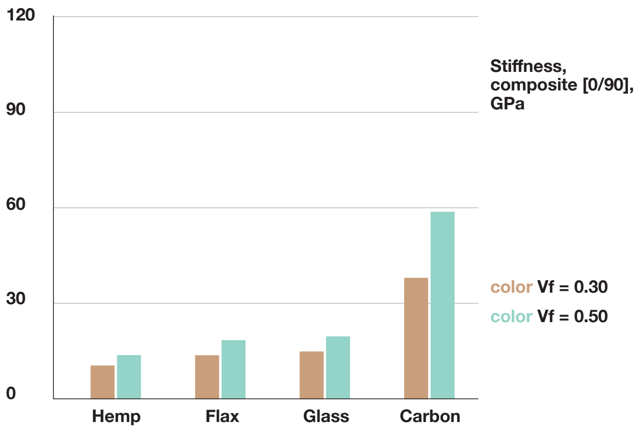
STIFFNESS [0° FIBERS], GPa	COMPOSITE, V_f =30%	COMPOSITE, V_f =50%
Hemp	16	24
Flax	22	34
Glass	23	37
Carbon	71	117



The stiffness values for composites with aligned fibers (fiber direction 0°) are all very high. Those for the flax fiber composite are comparable to those for the glass fiber composites. For all composites the stiffness increases with fiber volume fraction, as indicated by the equation for stiffness.

Stiffness for woven fabric composites

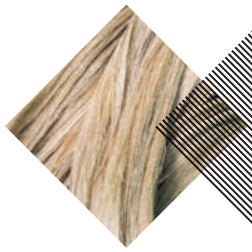
STIFFNESS [0° /90°], GPa	COMPOSITE, V_f =30%	COMPOSITE, V_f =50%
Hemp	9	13
Flax	12	18
Glass	13	19
Carbon	37	59



The stiffness values for for composites with woven fabrics (fiber directions 0° and 90°) are all medium-high. It can be noted that these values are slightly more than one half of the values for aligned fiber composites. The stiffness values for flax fiber composites are comparable to those of glass fiber composites. For all composites the stiffness increases with fiber volume fraction, as indicated by the equation for stiffness.

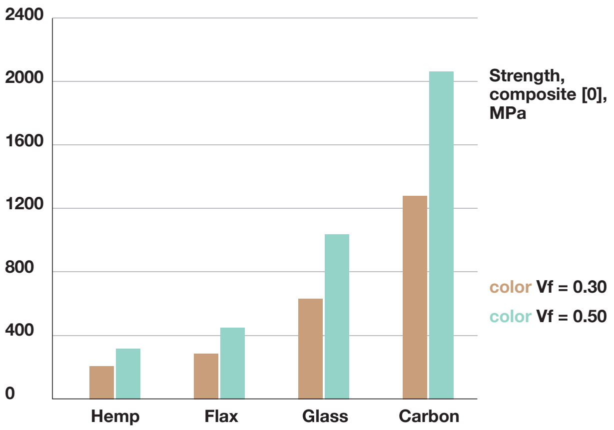
Stiffness for non-crimp fabric composites and for random mat composites

These stiffness values can be calculated using the relevant fiber orientation factors, in the same way as for the woven fabric composites. The values are similar but lower than those for the woven fabric composites, and show the same trends with respect to fiber type and to fiber volume fraction. For fiber volume fractions of 30% and 50%, the stiffness values for non-crimp fabric composites are approximately 56% of those for the woven fabric composites, and the stiffness values for random mat composites are approximately 78% of those for the woven fabric composites.



Strength for aligned fiber composites

STRENGTH [0° FIBERS], MPa	COMPOSITE, V_f =30%	COMPOSITE, V_f =50%
Hemp	215	325
Flax	275	425
Glass	635	1025
Carbon	1235	2025



The strength values for composites with aligned fibers (fiber direction 0º) are all very high. The flax and hemp composites have relatively low strengths compared to glass and carbon composites, which is due to the low strength values of flax fibers and hemp fibers as such. When strength is related to density, flax and hemp composites are closer to glass fiber composites, see below. For all composites the strength increases with fiber volume fraction, as indicated by the equation for strength.

Strength for woven fabric composites

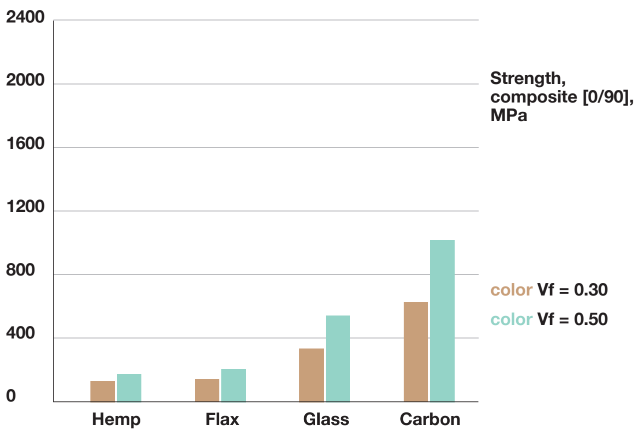
STRENGTH [0°/90°], MPa	COMPOSITE, V_f =30%	COMPOSITE, V_f =50%
Hemp	125	175
Flax	155	225
Glass	335	525
Carbon	635	1025

The strength values for composites with woven fabrics (fiber directions 0º and 90º) are all medium-high. It can be noted that the strength values are slightly more than one half of the values for aligned fiber composites. The flax and hemp composites have relatively low strengths compared to glass and carbon composites. For all composites the strength increases with fiber volume fraction, as indicated by the equation for strength.

HISTORY

In Denmark the Sailing Ship Owners Association for commercial trade in 1901 published a Handbook for Practical Seamanship (in Danish). It starts with about 60 pages on ropes, hawser-laid ropes and tow ropes, and related knots, all made out of hemp. The text describes the hemp and it properties [translation from Danish]:

“The hemp has considerable strength, and the fact that it easily takes up tar makes it well suited for uses at sea. The hemp loses some of its strength by being tarred, but the advantage... tarred hemp will resist rotting much better than untarred hemp. The ropes will be about 12 to 20% heavier by tarring. But a rigging of hemp, made of good materials and well maintained, has sometimes been used 18 to 20 years on a ship, while an iron wire rigging hardly dares be considered reliable for more than 12 to 15 years.”



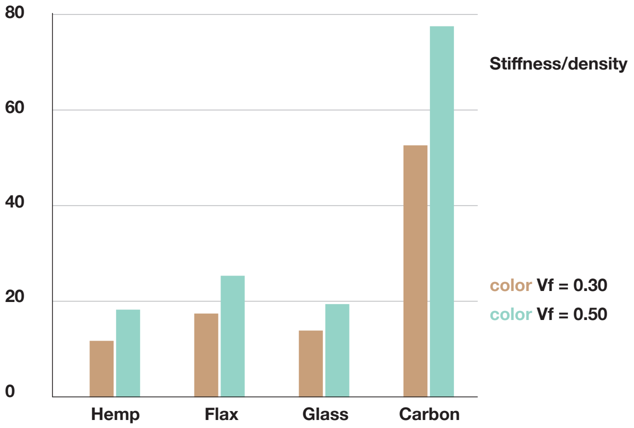
Strength for non-crimp fabric composites and for random mat composites

These strength values can be calculated using the relevant fiber orientation factors, in the same way as for the woven fabric composites. The values are similar but lower than those for the woven fabric composites, and show the same trends with respect to fiber type and to fiber volume fraction. For fiber volume fractions of 30% and 50%, the strength values for non-crimp fabric composites are approximately 56% of those for the woven fabric composites, and the strength values for random mat composites are approximately 78% of those for the woven fabric composites.

Stiffness relative to density for composites

The flax and hemp fiber composites perform relatively better in applications where the weight of the component is of importance, because of their relatively low densities. If the component, e.g. a rod, is loaded in tension, the material parameter describing the material-efficiency with respect to weight is the stiffness divided by density, also called the specific stiffness for tension. For a plate or a beam, where (only) the thickness of plate or beam can be varied, the material efficiency parameter is stiffness to 1/3 power divided by density, also called the specific stiffness for bending. Typical values are listed in the tables, where the stiffness relates to aligned fiber composites and values are in unit GPa, and the density values are in unit g/cm³.

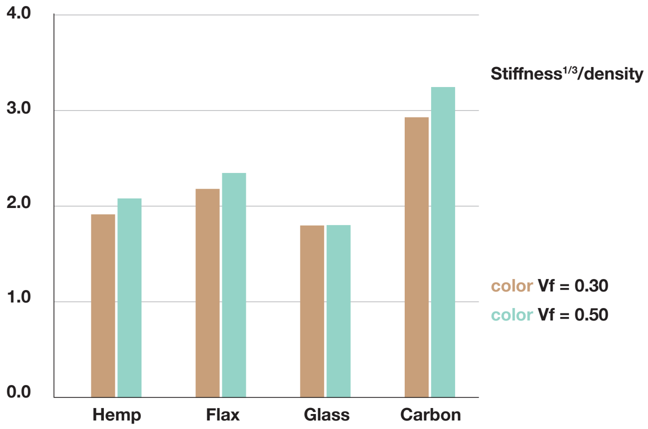
ROD, STIFFNESS/DENSITY	COMPOSITE, V_f =30%	COMPOSITE, V_f =50%
Hemp	12	18
Flax	17	25
Glass	14	19
Carbon	52	78



PLATE, BEAM, STIFFNESS$^{1/3}$/DENSITY	COMPOSITE, V_f =30%	COMPOSITE, V_f =50%
Hemp	1.9	2.1
Flax	2.2	2.4
Glass	1.8	1.8
Carbon	3.0	3.3

For a rod under tension loading, the hemp fiber composites have a material efficiency comparable to glass fiber composites, while the flax fiber composites perform somewhat better than glass fiber composites. For a plate or a beam under bending loading, both the flax and the hemp composites clearly have a better material efficiency than the glass fiber composites.
Figure 6 shows the plate/beam-parameter for all composites as a function of the full range of fiber volume fractions.

It is clear that flax and hemp fiber composites perform better than glass fiber composites, and this is due mainly to the relatively low densities for the flax and hemp composites.



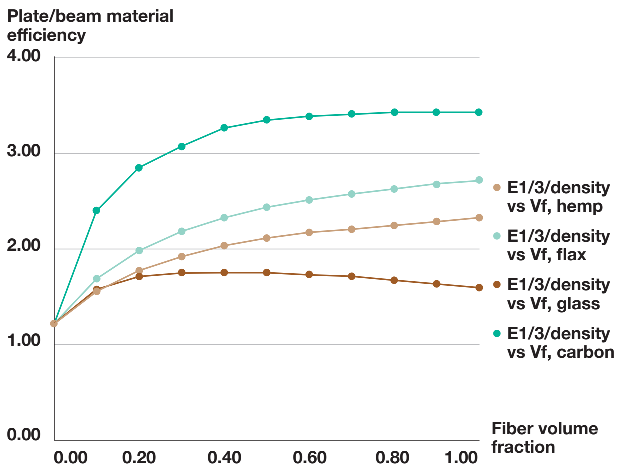
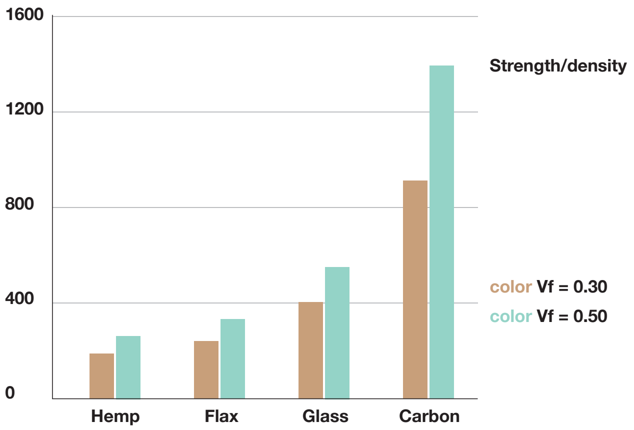


FIG. 6 **Plate/beam parameter versus fiber volume fraction for all four composites**

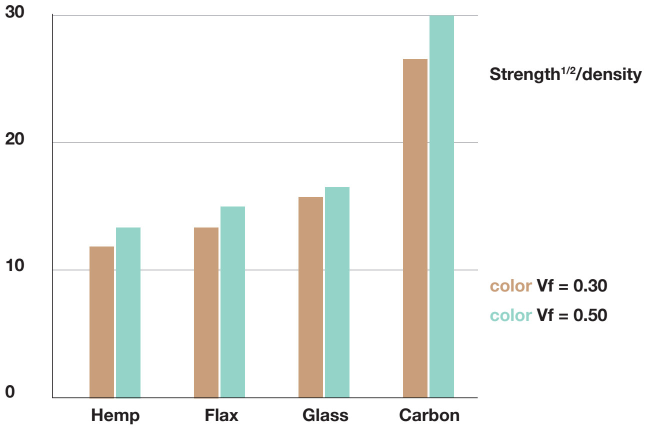
Strength relative to density for composites

Due to their relatively low densities, the flax and hemp fiber composites also perform relatively better for strength in applications where the weight of the component is of importance. If the component, e.g. a rod, is loaded in tension, the material parameter describing the material-efficiency with respect to weight is the strength divided by density, also called the specific strength for tension. For a plate or a beam, where (only) the thickness of plate or beam can be varied, the material efficiency parameter is strength to 1/2 power divided by density, also called the specific strength for bending. Typical values are listed in the tables, where the strength refers to aligned fiber composites and values are in unit MPa, and the density values are in unit g/cm³.

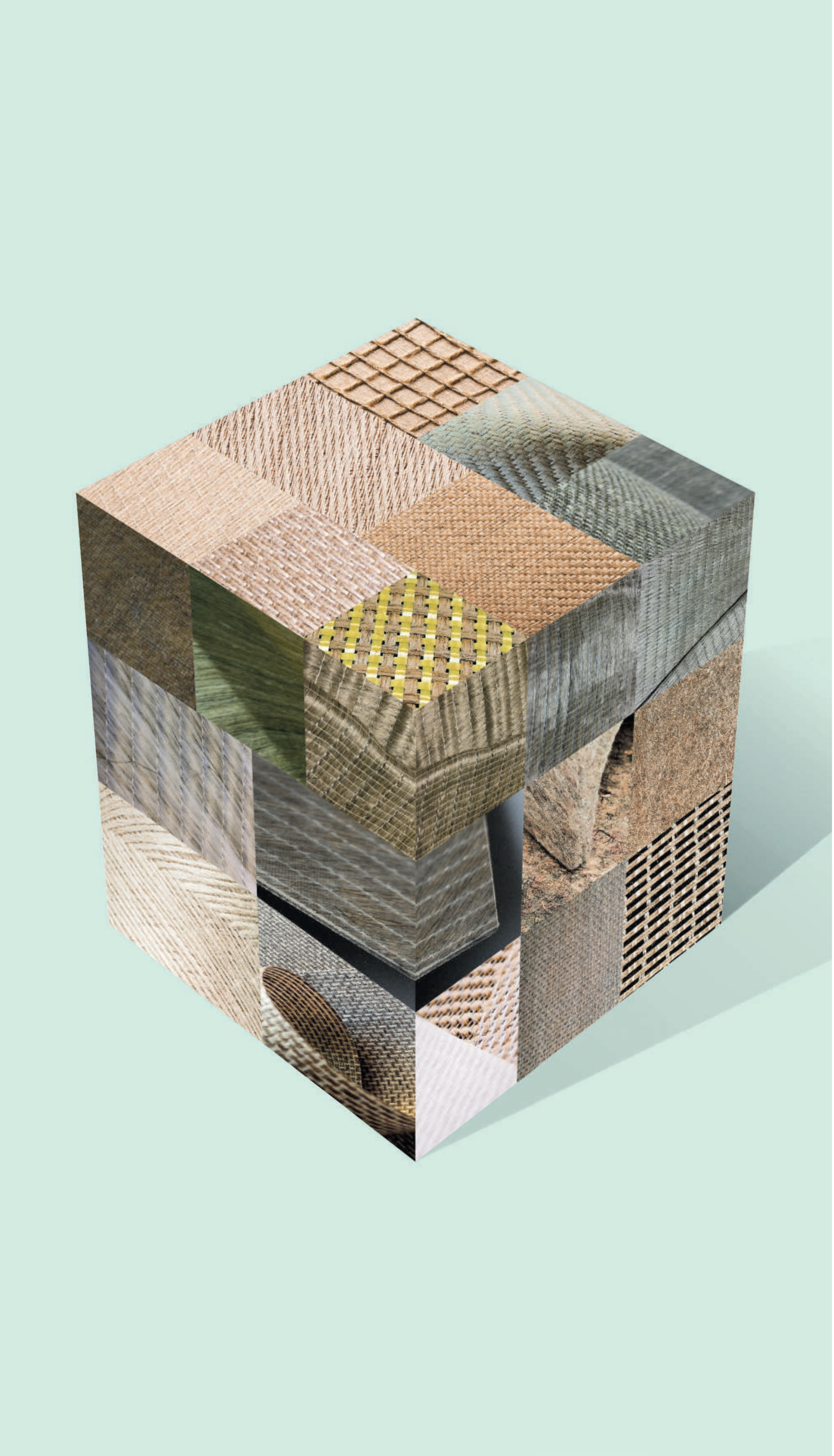
ROD, STRENGTH/DENSITY	COMPOSITE, V_f =30%	COMPOSITE, V_f =50%
Hemp	167	241
Flax	213	315
Glass	392	539
Carbon	895	1350



PLATE, BEAM, STRENGTH$^{1/2}$/DENSITY	COMPOSITE, V_f =30%	COMPOSITE, V_f =50%
Hemp	11	13
Flax	13	15
Glass	16	17
Carbon	26	30



For a rod under tension loading, the hemp and the flax composites have material efficiencies for strength, which are somewhat lower than those for glass fiber composites. For a plate or a beam under bending loading, both the flax and the hemp composites clearly have material efficiencies for strength, which are comparable to those for glass fiber composites.



III

Biosourcing: What Are the Available Reinforcements on the Market?

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PhD researcher at the department of materials engineering at KU Leuven.

3.1 Types of reinforcements

Composite manufacturing always involves the mixing of fibers and matrix. The manufacturing process is closely linked to the form or architecture in which the fibers are provided. Over the years, a broad spectrum of architectures has been developed for flax fibers. Due to the less-developed extraction process for hemp fibers and stringent agricultural regulations, the architectures produced with these fibers are still limited. Two main classes of possible architectures exist:

1. Dry preforms contain only fibers. The matrix is added later in the production process, after which the part is consolidated.
2. Pre-impregnated preforms, also called prepregs, contain both fibers and matrix. The matrix is already in intimate contact with the fibers, and only consolidation* is necessary to form the final part.

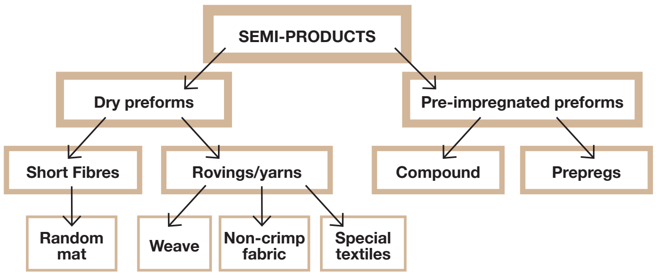


FIG. 1 **Different types of semi-products: dry and pre-impregnated preforms.**

Within these two large classes, there are a variety of commercially available fiber architectures that have already proven their use in several applications. In the 2012 and 2014 editions of this publication series, many preforms were discussed. Since then, preform development and (commercial) production has continuously improved, taking into account the specific requirements for composites. Nowadays, there is a clear difference between technical textiles for composites and the non-technical textiles used (for instance) in clothing. Moreover, newer preforms and special textiles have recently entered production. The next paragraph gives an overview of available preforms and the most recent developments in this area.

** For thermoplastic prepregs, the melting of the matrix and its even distribution in between the fibers is also considered in this consolidation process*

3.2 Available preforms and recent developments

Dry preforms

A preform is considered as “dry” when no matrix materials are present in the preform. Depending on the length and positioning of the fibers, different architectures can be produced.

→*Short fibers*

Short fibers come in a variety of lengths, but are generally shorter than 150 mm. They can be obtained by cutting long flax fibers or by collecting the byproducts of scutching and hackling, called tow. Cutting is usually done very early in the extraction process, after scutching. Shorter fiber lengths will decrease the mechanical properties of the composites (this is a general rule for all types of fibers, including glass and carbon fibers). Typically, this type of short fiber is used to increase the stiffness of a polymer to limit deformations of a specific part after production (dimensional stability), or during use. Because the fibers have not undergone the complete extraction process, fiber purity is limited to values between 95 and 99%, due to shive particles that have not been fully removed. Cut short fibers can be used to produce compounds, as needed in injection molding or bulk molding, whereas the tow is used for random mats.

→*Random mats*

Dry preforms with a very limited degree of fiber orientation are called random mats or nonwovens. These mats are easy and cheap to produce but, due to their limited fiber orientation, lead to rather low mechanical properties of the resulting composites. Often the production process leads to some preferential orientation of the fibers in the machine direction and so the result is not completely random; nevertheless, they are still called random mats. Depending on the production process, the areal density can vary between 300 and 2,400 g/m². An advantage of random mats is their excellent drapability, which avoids wrinkling defects. However, the dry strength of these mats is usually low, so rupturing of the preform is likely to occur in very complex mold designs.
Impregnation with a thermoset resin is possible using vacuum infusion or RTM. Typical random mat areal densities for combination with thermoset resins lie around 300 – 400 g/m². Permeability of random mats is low compared to other preforms due to random ordering of the fibers, which forces the resin to follow a tortuous path. Therefore, the achievable volume fraction is also low because the ordering creates a less dense structure than when the fibers are oriented in bundles, as in weaves.
Thermoplastic parts can be produced by hybrid mats that contain both polymer fibers and flax or hemp fibers. The mat can be heated to a temperature above the melting point of the polymer and shaped in a cold press to consolidate the part. The stiffness of these parts is limited to approximately 5 Gpa, and strength usually fluctuates around 50 MPa.

© Ecotechnilin/Fibrimat

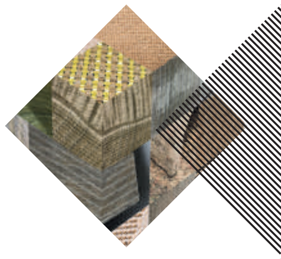
FIG. 2 **Non-woven dry flax fiber mat.**

→*Unidirectional dry preforms*

Whereas random mats have no form of fiber orientation, unidirectional (UD) preforms are at the other extreme, containing only fibers oriented in one direction. UD preforms come in the form of a continuous tape containing no binders, and are stabilized by a specific process that uses only substances already present in the fibers. This type of preform can be stacked at different angles, which makes it possible to “tune” the composite properties accurately in different directions. Areal densities vary between 50 and 200 g/m². For a unidirectional composite with a fiber volume fraction of 40%, the stiffness can be as high as 28 GPa and the strength, up to 250 MPa.

© Linéo / FlaxTape

FIG. 3 **Dry unidirectional preform of flax fibers.**



→*Rovings and yarns*

In contrast to synthetic fibers, flax and hemp fibers are not continuous. They have a certain length that is determined by the growth of the flax plant. However, for further processing such as weaving, braiding or filament winding, continuous filaments with a minimum strength are required. To achieve this, the flax or hemp fibers, which have a finite length, are spun into rovings and yarns. During spinning, a certain amount of twist is applied to the fibers to keep them together, using frictional forces. A low twist results in rovings, while a high twist results in yarns.
The higher the twist, the stronger the dry roving or yarn will be, and the easier it is to process in subsequent operations such as weaving, braiding or filament winding. However, this is only true for the dry preform, as increased twist also results in a misorientation of the fibers, which leads to a decrease in composite stiffness and strength. This is shown in Figure 4, where the decrease in stiffness for a UD composite made of impregnated flax fiber rovings with increasing twist is shown. Traditional textile yarns can have twist angles higher than 20°, which means that the composite stiffness is drastically reduced compared to the UD reference. Twist is usually expressed as a number of revolutions per meter, with typical values of 280 twists per meter for standard yarns and 40 twists per meter for rovings. The twist angle can be calculated from this number if the diameter of the roving or yarn is known. For the same twist number, thicker yarns will show a more pronounced decrease in performance compared to thinner yarns.

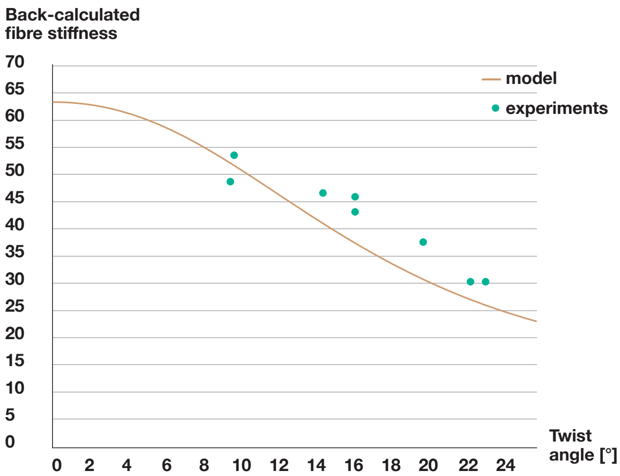


FIG. 4 **The solid line shows the theoretical influence of the twist angle on the stiffness of a UD composite containing flax yarns. xperimental values are also shown. The “zero” twist value is for a UD flax composite using yarns without any twist. The other values are for UD-composites using yarns with increasing degree of twist. [1]**

What are the latest innovation trends for flax & hemp fiber preforms?

Reinforcements based on flax and hemp fibres are continuously being developed and improved. Ten years ago, the number of architectures for composites made with these fibres was very limited and nearly identical to what was available on the non-technical textile market. In 2018, flax and hemp fibres are commercially available in nearly any possible arrangement, dry or pre-impregnated, from short fibres to flax fibre weaves, hybrid architectures with synthetic fibres and special grid structures.
In hybrid reinforcements flax & hemp fibers combine their remarkable properties such as, thermal and acoustic insulation and vibrational damping with synthetic high-performance fibers creating composite materials with unique properties.
The composite performance of the fibres has also increased significantly due to the use of low-twist rovings and low-crimp weaves enabling their use in semi-structural and structural applications.

When the twist number is too low, the roving would become too unstable for further processing without counter measures. However, to improve the composite properties, roving producers are continuously striving for lower twist numbers. One method currently under investigation to stabilize even lower twist rovings is to wrap a continuous filament around the roving. This does not increase the twist and provides the roving with a sufficiently high tensile strength to be processed. Another method is the partial dissolution of certain fiber components that act as a glue between the fibers in the roving. This glue then provides the necessary strength for further processing.
Unidirectional composites made with rovings have excellent stiffness and strength. A stiffness of approximately 28 GPa and a strength of 313 MPa for a volume fraction of 40% is achievable.

© Safilin / Tex 400 roving

FIG. 5 **Flax fiber roving with a linear density of 400 tex.**

Both rovings and yarns are available in different linear densities. The linear density is defined as the mass of the roving or yarns per unit length. A common unit to express this is "tex", which is the mass in grams per 1,000 meters of length. Rovings and yarns of 200, 400, 1,000 and 2,000 tex are the golden standards, although other tex values can be produced as well.

→*Weaves*

Weaves are textiles where fibers are strongly oriented in different directions. Weaves are produced by interlacing rovings or yarns in two perpendicular directions, using a specific pattern. The machine direction is called the warp direction and the weft direction is perpendicular to it. A large variety of patterns exist, leading to different mechanical properties, stability and drapability. The yarns that are used can differ in linear density and twist in the two directions, which also leads to different weave properties. The last parameter that can be altered is the number of warp and weft threads per unit length.
In the past, weaves for composites were almost always produced with highly twisted yarns, and the difference with traditional non-technical weaves did not exist. Nowadays, weaves for composites are very frequently produced using low-twist rovings specifically developed for composite applications.
It is important to note that rovings not only decrease the misorientation as outlined above, but also produce a secondary effect: the crimp of the fabric is reduced. Crimp is defined by Equation 1 and expresses the "waviness" or inclination of the yarns/rovings in the fabric. The higher this number, the more pronounced the waviness. Here again, this is a form of misorientation of the yarns/rovings, and thus of the fibers.

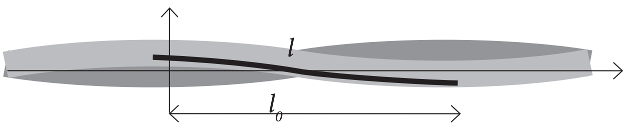
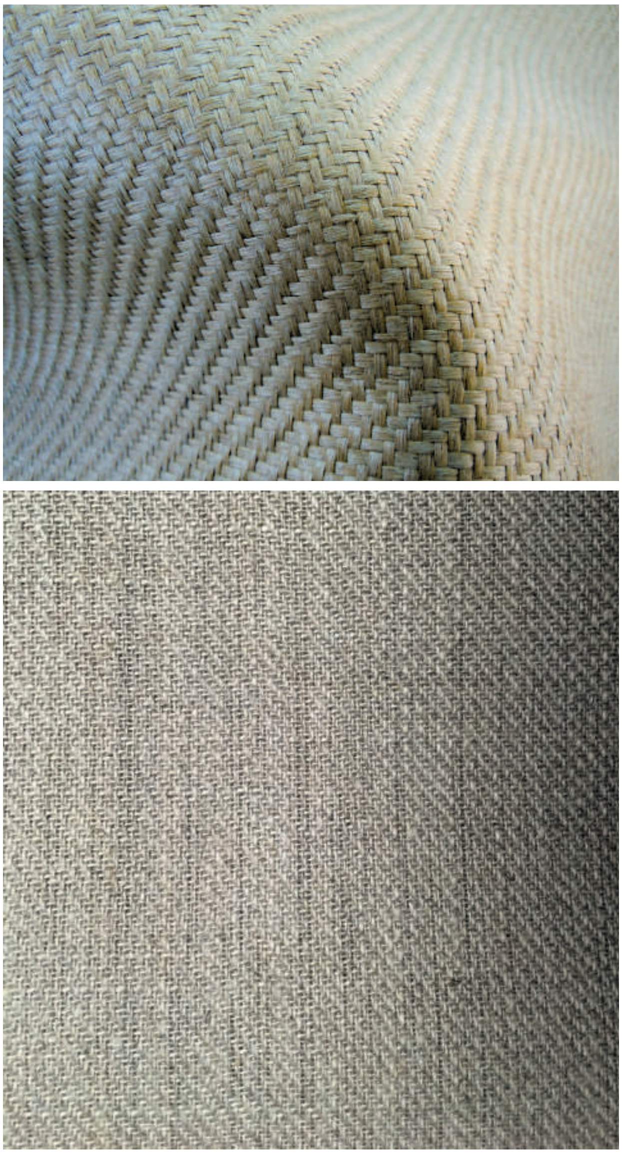


FIG. 6 **Parameters that define crimp.**

Here, l is the length of the yarn/roving in the unit cell and l0 is the length of this unit cell, shown in Figure 6.
Highly twisted yarns are very compact and round, which leads to a high crimp of the weave. In contrast, rovings are less compact and can even be somewhat flattened by consolidation pressures. This leads to a lower crimp and also increases the composite properties. Altogether, the use of rovings has increased the performance of composite properties by almost 20%. A typical balanced, plain weave with a total fiber volume fraction of 40% can reach a stiffness of up to 11 GPa and strengths of 115 MPa when rovings are used. Twill or satin patterns decrease crimp even more, thus higher modulus and strengths are achievable.



© Groupe Depestele / LINCORE FF

© Flipts & Dobbels / 171209/FAB twill 2/2

FIG. 7 **Two roving-based twill 2/2 weaves.**

© Linéo/ FlaxPly

FIG. 8 **Plain balanced weave.**

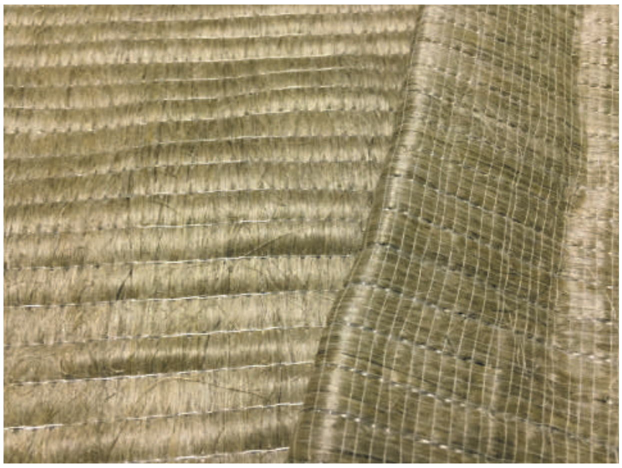
Weaves containing a very fine thread in the weft direction, which stabilize the rovings/yarns in the warp direction, are known as quasi-unidirectional weaves. Their mechanical properties (in the warp direction of the rovings) are generally very high, reaching a stiffness of 28 GPa and a strength of 220 MPa in the warp direction for a volume fraction of 40%.

© BComp / ampliTex quasi-UD

FIG. 9 **Quasi-UD weave; the stabilizing threads are visible in white.**

→*Non-crimp fabrics*

Different layers of unidirectional fibers, possibly oriented at different angles, can be stitched together to produce a non-crimp fabric (NCF). The layers can vary in orientation and areal density. Compared to weaves, the advantage of NCFs is that crimp is virtually nonexistent and there is more freedom to orient the fibers. Orientations, however, are limited to values between +/-20° and +/-90° relative to the machine direction for most layers except the outer ones, which can be oriented parallel to the machine direction (0°). Although flax fiber NCFs have long been limited to +/- 45° biaxial fabrics, the first 0°/90° NCF was recently introduced.



© Terre de Lin / Biorenforts - Biaxial 0°/90°

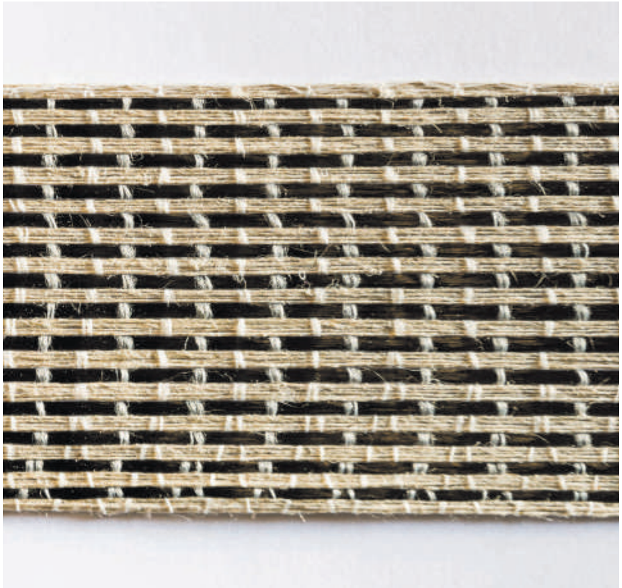
FIG. 10 **Biaxial 0°/90° non-crimp fabric.**

© BComp / ampliTex qSP5008

FIG. 11 **Biaxial +/- 45° non-crimp fabric.**

→*Special textiles*

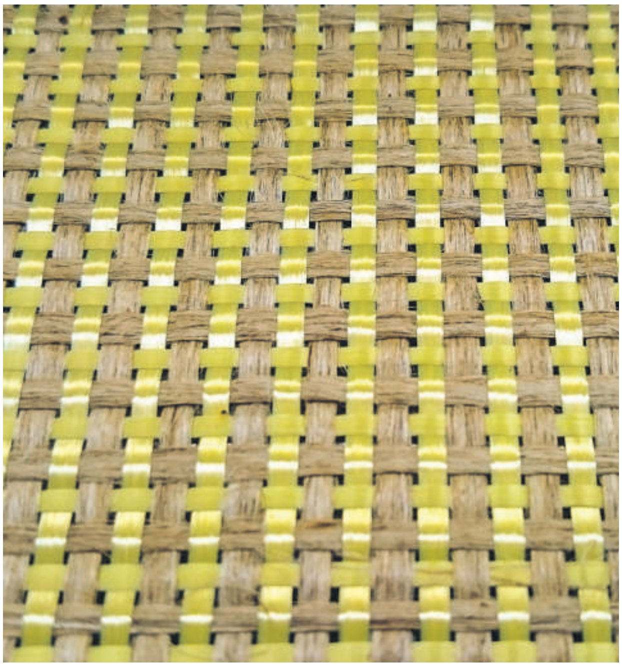
Next to their very high mechanical properties, flax and hemp fibers also exhibit other favorable properties that are of interest to the composite industry, such as thermal and acoustic insulation, vibrational damping and electromagnetic transparency (see Chapter 6). Innovative textiles have been developed recently to combine these properties with properties of other fibers used in composites, like glass and carbon fibers. Interestingly, when combining different fibers, the composite properties may be better than what is predicted by simple linear rules of mixture, the so-called hybrid effect.
In hybrid textiles, flax or hemp fibers are combined with one or more other fibers. A hybrid quasi-UD fabric containing 50 wt% carbon and 50 wt% flax fibers not only has an excellent mechanical behavior, but also provides significant vibrational damping, provided by the presence of the flax fibers. A unidirectional composite with a volume fraction of 50%, produced with this reinforcement, reaches a stiffness of 75 GPa and a strength of 613 MPa (in the fiber direction). Both fibers have very similar failure strains, leading to optimal performance of the hybrid composite. These hybrid carbon/flax textiles could also lead to more cost-efficient solutions for many composite parts.



© BComp / ampliTex Fusion UD

FIG. 12 **Hybrid flax/carbon fiber quasi-UD weave containing 52 wt% carbon fibers.**

Similarly, hybrid textiles containing glass, basalt and/or aramid fibers exist in different architectures. Aramid and other polymer fibers can be hybridized with flax to produce high-stiffness composites with excellent impact performance. Combining flax and E-glass fibers in composites can result in lighter composites while maintaining or even improving the stiffness compared to a 100% glass fiber composite.



© Groupe Depestele / Lincore HF

FIG. 13 **Hybrid flax/aramid fiber weave.**

Other special textiles that are currently available are open 0/90 grid structures which can be added as the outer layer in the composite part. The grid consists of coarse, relatively thick flax yarns that greatly increase the structural bending stiffness of the final part while adding very little mass, making it highly cost-efficient. The grids can be consolidated with virtually any textile reinforcement, both natural and synthetic. When in place, it also increases the damping and damage tolerance of the composites.
As the understanding of the mechanical behavior of hybrid composites progresses, it is expected that more and more complex architectures will be developed to tailor the properties of the composites. This is where flax and hemp fibers show their true potential. By complementing the properties of other fibers, high performance composites can be created for demanding applications.

© BComp / powerRibs

FIG. 14 **Dry grid structure on a quasi-UD weave.**

Pre-impregnated preforms

Pre-impregnated preforms are divided into two main classes. Short-fiber preforms are usually called compounds, while long-fiber preforms are called prepregs.

→*Compounds*

Dry short fibers can be mixed with a thermoplastic in an extrusion line, where a rotating screw generates shear forces. The compound is obtained by cutting the extrudate into small pellets. Compounds can also be obtained through the recycling of long-fiber composites by feeding them into a shredder, after which the shredded material is fed into the extrusion line. Typically, the length of the fibers is reduced by the shearing in the extruder. However, the length reduction seems to be less dramatic than for synthetic fibers such as glass, and eventually stops when a critical length is reached, unlike for glass or carbon fibers, which continue to decrease in length after every compounding step. This means that flax and hemp fibers could be recycled multiple times without losing too much of their mechanical properties.
By incorporating short fibers into a commodity thermoplastic such as PP, the stiffness can be increased significantly from 1 to 4 GPa and the strength, to 40 MPa. On the other hand, only a limited number of thermoplastics can be combined with flax and hemp fibers, due to their low degradation temperature of around 200°C. PP, PVC, PLA, ABS and PE all have low melting points and can be combined with flax and hemp fibers. The compounds produced are typically used in injection molding to produce intricate parts, or in extrusion to produce long profiles with constant cross-section.
Mixing short fibers with thermosets is less common, but can be done as well. The most common matrix systems in this case are polyesters and epoxies. Due to the lower viscosity of the resin, mixing is facilitated, and the required shear forces are minimal. The product is usually denoted as a bulk molding compound (BMC) and can be used in compression molding or thermoset injection molding.

→*Prepregs*

The dry preforms described above can also be combined with thermoplastic and thermoset matrices. Pre-impregnation of dry preforms is often preferred, as it allows the end-users of the preform to increase the ease of processing and decrease production times.
For random mats, the pre-impregnation process was already partially described. When (thermoplastic) polymer fibers are added during the production of the random mat, they are intimately mixed with the flax or hemp fibers. During further processing, heating will melt the polymer fibers, completing the impregnation process. The part can then be formed and consolidated by cooling. Currently, random mats containing PP and flax fibers are commercialized, although the process can be easily altered to include any other type of polymer fiber.
Impregnation of random mats with thermosets can be achieved by applying a liquid resin film on the dry preform, followed by compression of the preform and heating the thermoset to the B-stage. Nowadays, fully biobased pre-impregnated random mats based on thermoset furan resins are available. They are used frequently as skin layers for sandwich panels because of the fire-retardant properties of the furan resins.

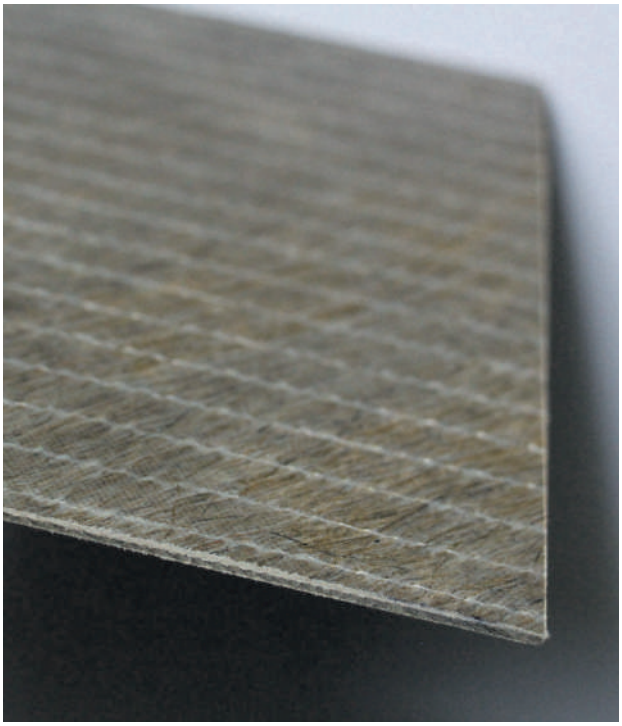
© Ecotechnilin / FIBRIPLAST

© Ecotechnilin / FIBRIPREG

FIG. 15 **(Left) Non-woven flax fiber mat pre-impregnated with PP. The mat consists of 50 wt% flax fibers and 50 wt% PP filaments, which are intimately mixed during production. (Right) Consolidated non-woven furan prepreg containing 30 wt% flax fibers used as skins in a sandwich panel.**

All other architectures are based on rovings or yarns, so they require a different method to mix the fibers with the matrix system.
Thermoplastics can be drawn into filaments. When these filaments are processed together with flax or hemp fibers, a roving or yarn containing both materials is produced.
In co-wrapping, matrix filaments are wrapped around the roving or yarn, whereas in commingling, the filaments are added during doubling, which embeds them into the roving or yarn. Commingling results in a more intimate mix of fibers and matrix, and facilitates impregnation during further processing. Flax/PP and flax/PLA rovings are commercially available as well as their weaves, either in balanced form or as a quasi-UD. When consolidated into a composite, a balanced weave with commingled flax/PLA rovings has a stiffness of 14 GPa and a strength of 100 Mpa, for a fiber volume fraction of 35%. Non-crimp prepregs are made in a similar way, but perform better mechanically, due to the absence of crimp.

© Terre de Lin / Biorenforts



© Dedienne Multiplasturgy group / Flaxcomp SP

FIG. 16 **Non-crimp flax fiber/PP prepreg before and after consolidation.**

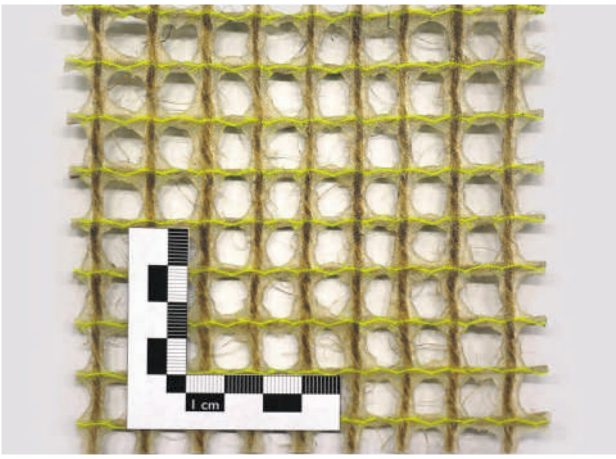
Impregnation can also be achieved by placing the weave between thermoplastic films or by spraying a reinforcement with a thermoplastic powder that, after melting, sticks to the fibers. Of course, the mixing of fibers and matrix is even less intimate than for the co-wrapped rovings, and can lead to impregnation difficulties and defects during consolidation.

© Flipts & Dobbels / 171209/IMP twill 2/2

FIG. 17 **Thermoplastic woven flax fiber prepreg with 40wt% PP.**

© Dehondt Composites / TwinFlax P-preg

FIG. 18 **Woven flax fiber prepreg with polyamide 11 resin.**



© BComp / powerRibs 0/90 prepreg

FIG. 19 **Prepreg of a flax fiber grid structure with PP. The presence of PP facilitates the attachment of the grid to thermoplastic composites.**

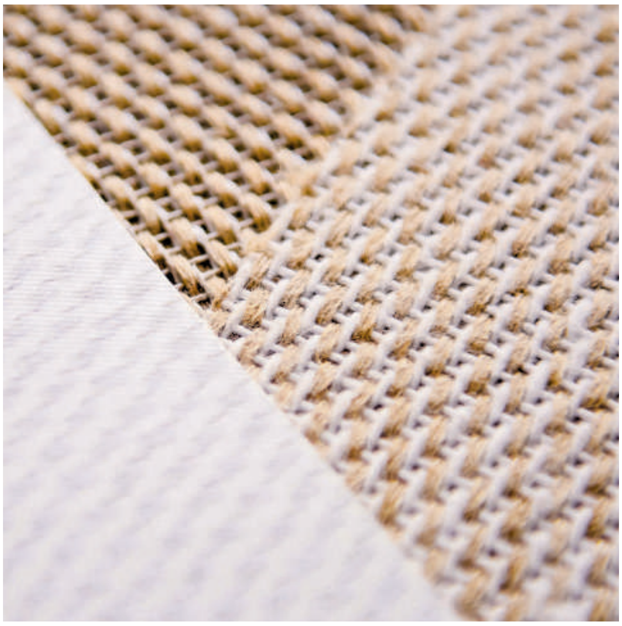


FIG. 20 **Woven flax fiber prepreg where PLA filaments are used in combination with flax rovings or yarns. During consolidation, the PLA yarns will melt and impregnate the fibers. Note that after this process, the composite contains only fibers in one direction.**

Finally, prepreg weaves can also be produced by integrating the matrix filament in the weft or warp direction. This type of weave is rather new, so further research on impregnation quality, formability and mechanical properties is required.
Thermoset resins are combined with long-fiber preforms by using a hot-melt process. A thermoset (resin + hardener) is distributed over the reinforcement and, because of the low viscosity in the non-crosslinked thermoset resin, only a small amount of pressure is needed to impregnate the preform. The material is then heated for a very short period to initiate the cross-link reaction, but the process is interrupted in the B-stage of the thermoset by rapid cooling. This leaves the prepreg tacky, but still handleable and formable. The prepregs must be stored at low temperatures to keep the reaction from progressing. During manufacturing, the impregnation and compaction process is completed by applying higher pressures (and temperatures), and the part fully cures.
Because they are used mainly in high performance applications, UD materials are often combined with high performance thermoset polymers such as epoxy. Many thermoset-based UD prepregs exist, because they are preferred over the dry UD preforms due to the rather difficult handling of the latter. Consolidated composites based on these UD prepregs perform as well as their dry counterparts, which are impregnated by vacuum infusion or resin transfer molding.
Pre-impregnated weaves are available in all architectures, balanced and UD. Areal densities of these prepregs range between 150 and 550 g/m². The stiffness of quasi-UD weaves can reach 35 GPa, with a strength of 330 MPa in the warp/fiber direction for a fiber volume fraction of 60%.

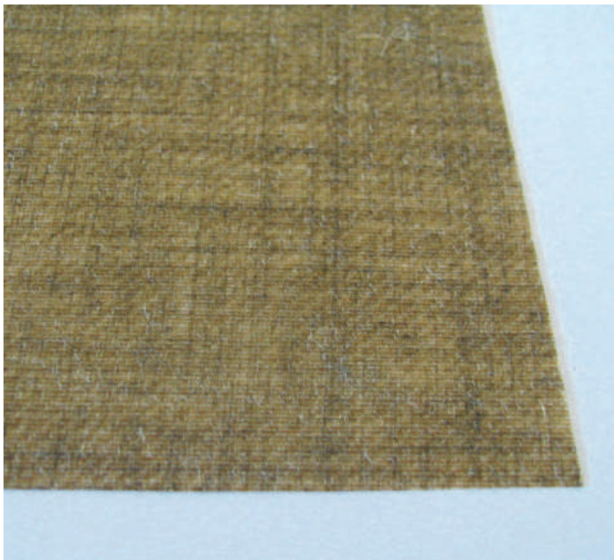


FIG. 21 **Pre-impregnated weave containing 50 vol% flax fibers in the form of a balanced twill 2/2 weave and 50 vol% epoxy. [2]**

Conclusion

Over the past years, flax and hemp preforms and prepregs have continuously been improved towards their performance in composite applications. A clear distinction now exists between non-technical textiles that are optimized for clothing, apparel and household applications, and the technical textiles that are specifically developed for composite applications. Further developments are ongoing to find more optimal fiber architectures, however. Hybrid textiles are rapidly becoming more widespread, since they can lead to much higher performance by complementing synthetic (glass, carbon) reinforcements with exceptional flax and hemp fiber properties.

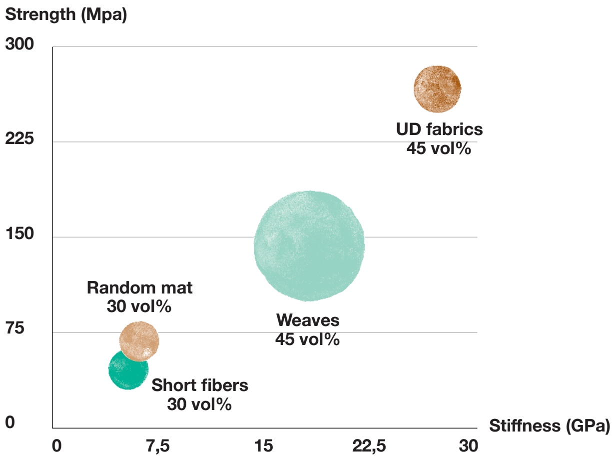


FIG. 22 **Overview of the stiffness and strength for different types of preforms. The theoretically achievable properties are mentioned. The values for UD fabric are in the fiber direction, while the values for weaves correspond to the properties for both warp and weft directions. [1]**

This chapter provided the reader with an overview of a number of reinforcements that are available on the market, along with some guide values for the mechanical properties of their composites, and stiffness and strength values for the preforms discussed. Figure 21 provides a general overview of the composite properties that are theoretically achievable using different architectures. In Figure 23 and Figure 24, an overview is given for the measured stiffness and strength of epoxy-matrix composites reinforced with different flax preforms. The higher the degree of flax fiber orientation in the preform, the higher the resulting composite properties will be. Unidirectional materials possess the highest stiffness and strength, followed by the 0°/90° UDs in the form of non-crimp fabrics or laminated UD layers (cross-plies). Balanced weaves and random mats have the lowest properties, but provide a stable preform to reinforce the composite in several directions.

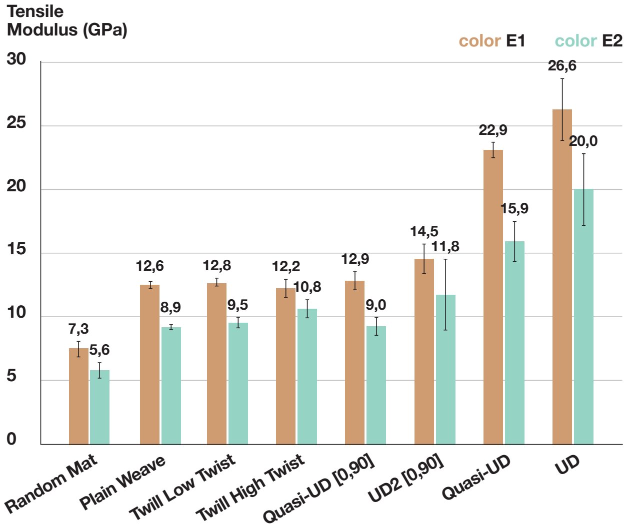


FIG. 23 **Overview of the stiffness for epoxy-matrix composites reinforced with different types of flax preforms. The values for UD fabric are in the fiber directions, while the values for the balanced weaves are the properties for both warp and weft direction. All results were normalized to a volume fraction of 40%, except for random mats, which were normalized to 30%. [2]**

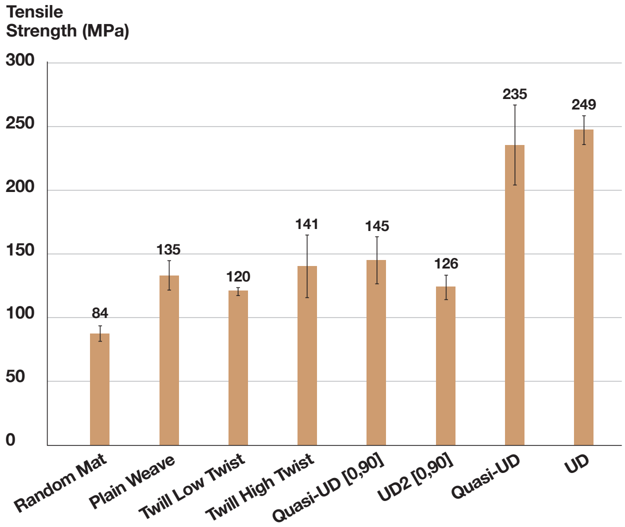


FIG. 24 **Overview of the strength for epoxy-matrix composites reinforced with different types of flax preforms. The values for UD fabric are in the fiber directions, while the values for the balanced weaves are the properties for both warp and weft directions. All results were normalized to a volume fraction of 40%, except for random mats, which were normalized to 30%. [2]**

Overview of the suppliers, processors, research institutions, universities and innovation platforms in Europe, related to flax and hemp fibers.

(For a complete list with all contact details the reader is referred to www.europeanflax.com)

CELC Technical Section Members

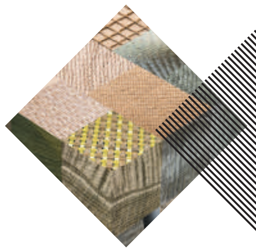
Flax and hemp fiber producers

Suppliers	Country
Brille	Belgium
La Chanvrière (hemp)	France
Decock SA	France
Groupe Depestele	France
La Liniere	France
Lin 2000	France
Procotex	Belgium
SA Jean Decock	France
Spillebeen	Belgium
Teillage de Lin du Neubourg	France
Terre de Lin	France
Van de Bilt	Netherlands
Van Robaeys Freres	France
Verhalle vlasbedrijf NV – Flax box	Belgium

Suppliers of the different preforms of flax & hemp fibers

Dry preforms	Supplier(s)	Country
Yarns & Roving	Safilin Groupe Depestele Linificio e canapificio nazionale	France France Italy
Random mat	Ecotechnilin	France
Unidirectional	Linéo	France
Weave (incl. quasi-ud)	BComp Flipts & Dobbels Groupe Depestele Dehondt Composites	Switzerland Belgium France France
Non-crimp fabrics	BComp Terre de Lin	Switzerland France
Braid	BComp	Switzerland
Grids	BComp	Switzerland

Prepregs	Supplier(s)	Country
Compounds	Ecotechnilin Groupe Depestele	France France
Yarns & Roving	Dehondt Composites Groupe Depestele	France France
Random mat	Ecotechnilin	France
Unidirectional	Linéo	France
Weaves (incl. quasi-ud)	BComp Culture In Dehondt Composites Groupe Depestele Linéo Terre de Lin	Switzerland France France France France France
Grids	BComp	Switzerland



HISTORY

Alexander the Great (256-323 BCE) has gone down in history as one of the greatest strategists the world has known. His armor, almost as famous as his horse Bucephalus, was made not of metal but of layers of laminated linen cloth (Pliny), forming a composite material! This sort of protection was used by many warriors, all famous for their mobility on the battlefield. It was made of 11 to 20 layers of linen fused with a linseed oil-based bonding agent and then compressed during the drying process: the first composite material in history, with virtues similar to that of Kevlar®! Thanks to the strength, rigidity and the ability of flax fibers to absorb vibration, this extremely light material, called linothorax, was able to stop arrows. This revolutionary process came from the Etruscan port of Tarquinia where, in the 5th century BC, linen canvases that were soaked in linseed oil and then left to harden as they dried, were sold to navigators as sails that could withstand the worst storms.

Source: The Linen Book by CELC

Composite part producer

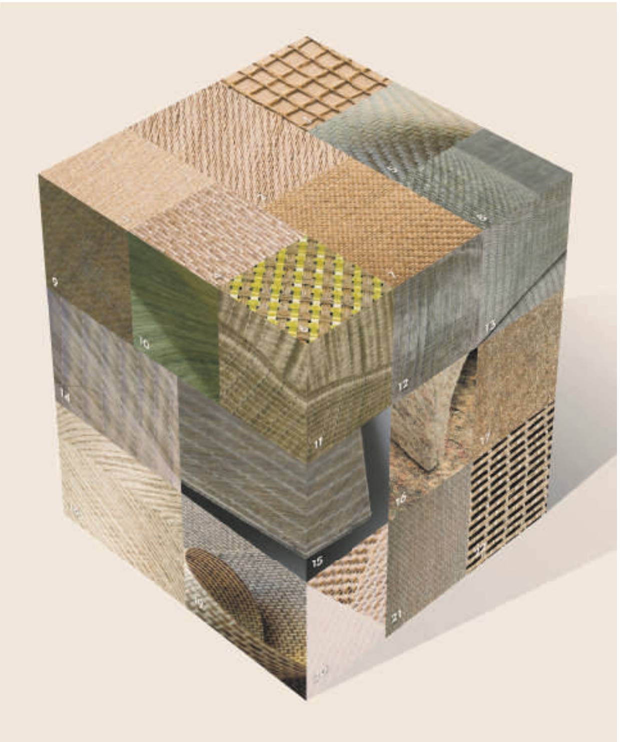
Dedienne Multiplasturgy group

Research centers, universities and innovation platforms

Name	Country
Arvalis	France
Centexbel	Belgium
Cetelor	France
CNRS Ensicaen	France
Danmarks Tekniske Universitet (DTU)	Denmark
ENSAIT	France
Fibres Recherche Développement	France
Helsinki University of Technology (TKK)	Finland
Hochschule Bremen (HSB)	Germany
IFREMER Materials & Structure GRP	France
IAR, the French Bio-Economy Cluster	France
IFTH	France
INRA – Université de Reims	France
Katholieke Universiteit Leuven	Belgium
Technische Universität Clausthal	Germany
Université de Bretagne Sud (UBS)	France
Universteit Gent	Belgium
Université de Lille	France
Université du Havre	France

Summary of the preforms shown in this chapter

Number	Supplier	Product name
1	Bcomp	ampliTex
2	Bcomp	ampliTex
3	Bcomp	powerRibs
4	Bcomp	ampliTex
5	Groupe Depestele	Lincore FF
6	Groupe Depestele	Lincore FF
7	Bcomp	ampliTex
8	Linéo	FlaxPly
9	Linéo	FlaxPreg
10	Linéo	FlaxTape
11	Terre de Lin	Biorenforts
12	Terre de Lin	Biorenforts
13	Terre de Lin	Biorenforts
14	Terre de Lin	Biorenforts
15	Dedienne Multiplasturgy	FlaxComp SP
16	Ecotechnilin	FibriPlast
17	Ecotechnilin	FibriMat
18	Salifin	Low-twist roving
19	Dehondt Composites	Twinflax
20	Culture In	Varian
21	Flipts & Dobbels	FlaxPreComp
22	Bcomp	AmpliTex Fusion UD



3.3 Datasheet template for preforms

The CELC European Scientific Council has developed several datasheet templates to promote standardized data reporting within the flax and hemp fiber industry. These sheets help manufacturers to ensure that their flax and hemp preforms are compliant with application specifications currently used in the composite industry. They also provide composite producers and users of these preforms with the information they need on the preform characteristics and achievable composite properties.

Datasheets are available for three different architectures: random mats, weaves and non-crimp fabrics. Each datasheet is divided into four sections:

A. **Identification** of the preform: name, origin of the fibers, etc.
B. **Characterization** of the preform, meaning the areal density, type of yarns used, weave style, etc. If a fiber treatment has been applied, then this should be included.
C. **Mechanical properties** of a composite produced with the preform: strength and stiffness in tension and bending, plus the recommended storage and processing conditions.
D. The final section of the datasheet is **optional** and can be used to provide additional information about other relevant properties such as compressibility, drapeability, damping capacity, etc.

All data sets are measured following international standards, in line with glass and carbon fiber benchmarks.

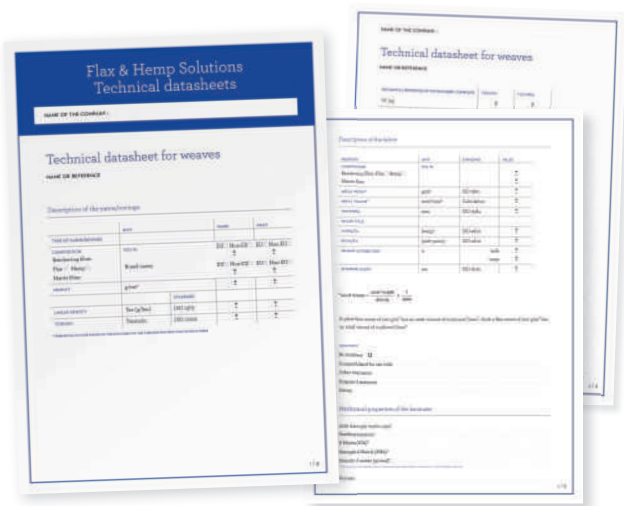


FIG. 25 **An example of the standardized datasheet for weaves to be used in combination with thermosets.**

More information about sourcing of fibers, preforms, prepregs and datasheets templates: **technical@europeanflax.com**

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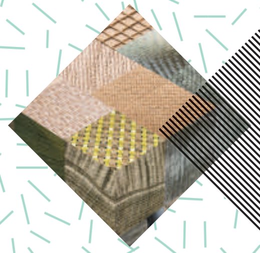

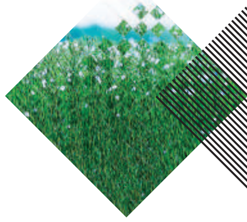

IV

How Do We Reliably Characterize the Mechanical Properties of Flax & Hemp Fibers?

Characterizing the longitudinal mechanical properties of fibres is vital to predict the behavior of composite materials under a given loading condition. Due to the complex hierarchical architecture of natural fibres this is challenging. This chapter describes these difficulties and proposes a method to accurately determine the fibre properties.

4.1 From single fibre properties to composite performance

In a single fibre test, a single fibre is loaded in tension to obtain the stresses and strains associated with it. These tests have long been used to assess the mechanical performance of fibres used in composite materials. In synthetic fibre composites these fibre properties enable the end user to predict the mechanical properties of the composite part. As an example, when the stiffness of a synthetic fibre, Ef, and that of the matrix, E_m have been determined, it is possible to predict the stiffness (in the fibre direction) of a unidirectional composite containing long (or continuous) fibres, with volume fraction, V_f, using equation 1. It expresses a linear relation between the fibre volume fraction and the composite stiffness.

$$E_c = V_f E_f + (1 - V_f) E_m$$

Strength-wise the same reasoning is valid. Once the strength of the fibres,σ_f, is known and if a matrix is used with a higher failure strain than that of the fibres, equation 2 is valid.
It should be noted that σ^*_m is not the ultimate strength of the matrix but the stress occurring in the matrix when the failure strain of the composite, $\varepsilon_{u,c}$, is reached. This stress can be calculated using Hooke's law expressed in equation 3 if the matrix has a linear elastic behavior in this region.

$$\sigma_c = V_f \sigma_f + (1 - V_f) \sigma^*_m$$

$$\sigma^*_m = E_m \, \varepsilon_{u,c}$$

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From these equations it can be seen that the value of E_f should be determined accurately to reliably predict the properties E_c. Single fibre tests are time consuming and difficult to perform technically since they require meticulous sample preparation and highly specialized strain measurement techniques [1]. These experimental difficulties lead to a rather high scatter in the measured fibre stiffness and strength properties [2]. This already indicates a first problem associated with single fibre tests.

The determination of natural fibre properties, however, should be approached even more carefully due to their heterogeneous microstructure as shown in Figure 1. Flax fibres grow in bundles inside the flax stem. When extracted and during further processing this bundle structure is retained more or less and is as such embedded in the matrix material during composite production. The bundles, called technical fibres, consist essentially of elementary flax fibres which are 10-20 µm in diameter and 2-3 cm long. They are glued together by a pectin-rich matrix to form the technical fibre. Technical fibers have a diameter of 70-100 µm and can be up to 1-1.5 m long. Figure 1 also reveals the reason flax fibres have very high stiffness and strength. Cellulose crystals, denoted as microfibrils, are aligned with the fibre axis. Since these crystals are very stiff and strong they dominate the mechanical behavior of the fibre.

To determine the technical fibre properties, as they are used in a composite, a first approach could be to test these technical fibres in tension using the single fibre method described above. Considering the fibre structure it has been proven, however, that tensile deformation of a technical fibre, being a bundle of elementary fibres glued together by a pectin rich layer, does not correspond to the actual deformation behavior in the composite [2,3]. In such a fibre test the elementary flax fibres can slide relative to each other thereby decreasing the apparent stiffness of the technical fibres. Also, strength of a technical fibre which is associated with the “quality” of the pectin glue is not indicative for the strength in the composite, as resin could partly replace the glue in regions where it was not present *(or had been removed or weakened during the retting process)*.

A more reliable value for the stiffness can be obtained by testing the elementary flax fibres. These single fibre tests have their use in fundamental scientific studies, for instance to assess the influence of variety, growth conditions etc… on the smallest building block of the flax plant. High scatter on the obtained mechanical properties, complex sample preparation, difficult testing procedures and the fact that elementary fibres are not present as such in composites, however, renders the test unsuitable for the composite industry.

Fortunately, there is method that can reliably predict the actual fibre performance in a composite. An impregnated fibre bundle test (IFBT) is performed by impregnating an amount of (technical) flax fibres with a resin, thus creating a composite material that contains many flax fibres. The material is then tested in tension and the properties E_f and σ_f of the fibres are derived from equations 1 and 2 (in their inverted form, see later eq. 5 and 6). This results in an accurate prediction of stiffness and strength as it is averaged by the hundreds of fibres that are embedded in the composite. It should be stressed that the IFBT is the only reliable way to characterize the fibre properties, as they are exhibited by the fibres in a composite. A detailed description of the method is given in the next paragraph.

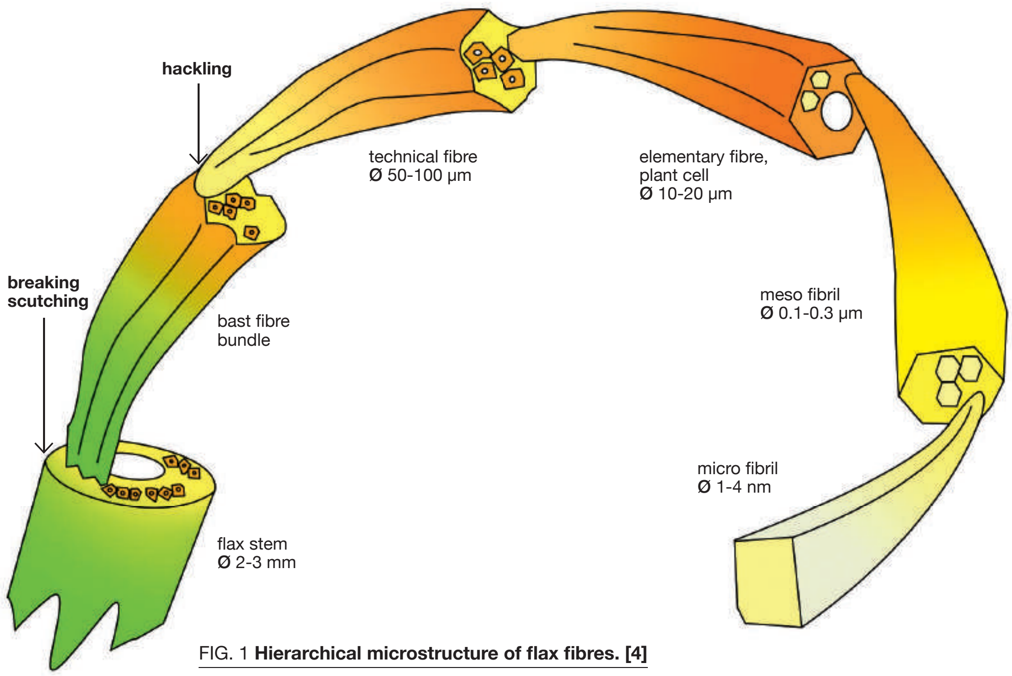


FIG. 1 **Hierarchical microstructure of flax fibres. [4]**

4.2 The IFBT method

The ISO 10618:2004 standard is a tensile test standard developed for carbon fibre reinforced plastics. Flax and hemp fibres have their own particularities when it comes to tensile testing. By modifying the ISO standard a methodological guide was created by the European Scientific Committee of CELC in which the specimen production and testing procedure of impregnated fibre bundles is described. These modifications were necessary as natural fibres typically exhibit a complex mechanical behavior and have a physically different appearance from carbon fibres.

In the presented method, a bundle of unidirectional (technical) flax fibres is used. The fibres are cut to a length of 25 cm dried for 24 hours at 60°C prior to impregnation. This is necessary because flax fibres always contain a certain percentage of moisture which can evaporate during composite production, thereby creating porosities. After drying, the fibres are placed in a mold cavity where a non-adhesive film was previously placed, as shown in Figure 2. A degassed resin is poured on top of the fibres, the film is folded and a counter-mould is placed on top. The entire set-up is then placed in a heated press for consolidation. Because the mass of the fibres, mf, placed in the cavities, is known, the fibre volume fraction can be set by controlling the volume of the composites, V_C. This is done by using a spacer to separate the two mould halves over a certain distance. The fibre volume fraction is then calculated using equation 4.

$$V_f = \frac{m_f \rho_f}{V_C}$$

A good estimate for the density of flax fibres, ρ_f, is 1.4 g/cm³. The value of 1.5 g/m² given in chapter 2 is an upper bound for the density of the fibres. It is rather important, however, to accurately determine the density of the fibres since small differences in density can lead to large differences in the calculated fibre volume fraction. Of course, a measurement of the fibre density on a specific sample can be done when in doubt. After the composite is consolidated, it is tested in tension and a stress-strain graph is obtained, as shown in Figure 3. As is seen in the figure and in contrast to carbon and E-glass fibre composites, the mechanical behavior of flax fibres is not fully linear elastic. There is a marked decrease in stiffness around 0.2 to 0.3 % strain. Thus, flax fibre composites are characterized by two moduli, E1 and E2 calculated between 0% and 0.1% strain for E1 and 0.3% and 0.5% strain for E2.

Once these moduli and the tensile strength of the composite have been determined the fibre properties can be back-calculated using equations 5 and 6, the inverted form of equations 1 and 2. Eq. 1 will of course result in two fibre moduli as well, as there are two composite moduli.

$$E_f = \frac{E_C - (1 - V_f)E_m}{V_f} \qquad \sigma_f = \frac{\sigma_C - (1 - V_f)\sigma^*_m}{V_f}$$

To stay close to the actual fibre performance in composite materials, it is advisable to use a matrix material that has good interfacial compatibility with flax fibres (epoxy resins are a good choice). A failure strain of at least two to three times the fibre failure strain is also required to ensure matrix failure does not cause the composite to fail.

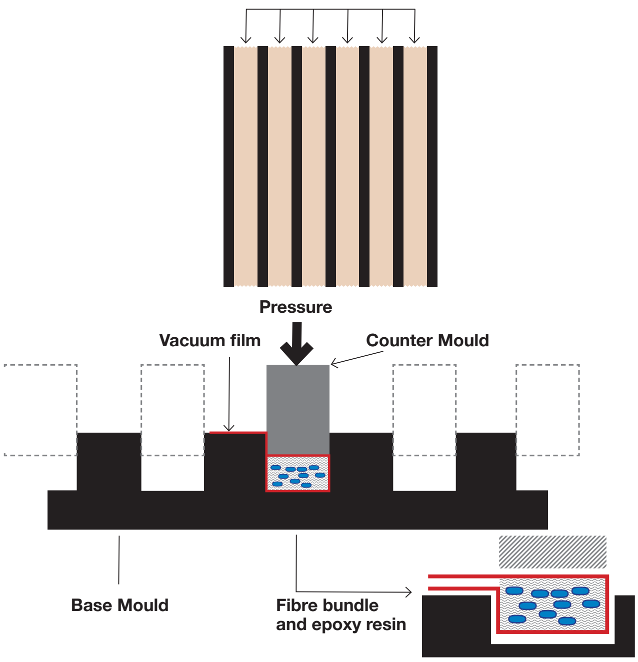


FIG. 2 **Schematic of the mould used to produce the IFBT samples. [2]**

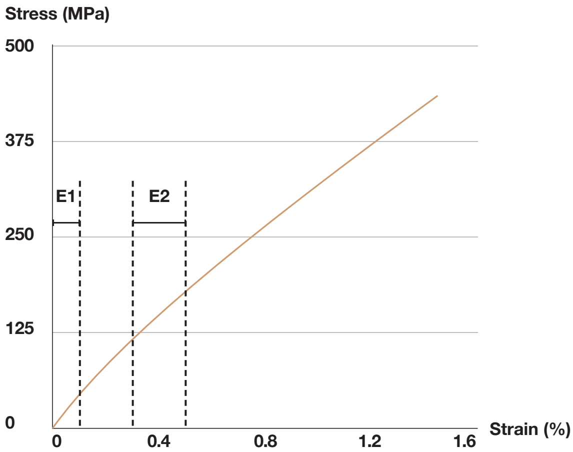


FIG. 3 **Typical stress-strain diagram for a unidirectional flax fibre composite. The regions where E1 and E2 should be determined are indicated. [2]**

4.3 Validation of the protocol and comparison to single fibre test properties

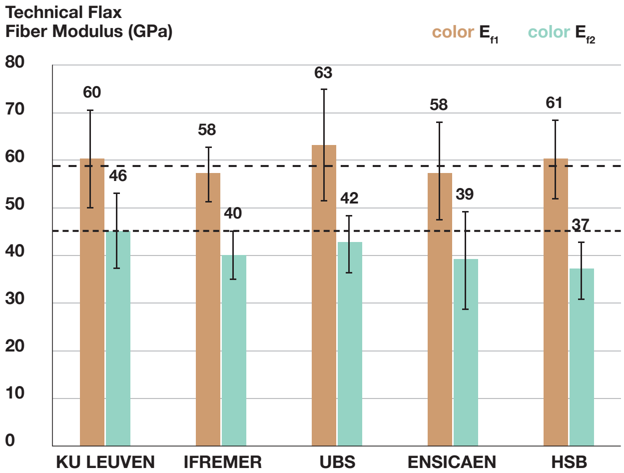
The repeatability and robustness of the test methodology outlined above has been demonstrated in a round robin test, organized by the European Scientific Committee within CELC, between five different European laboratories using flax fibres originating from the same batch. The batch underwent retting, scutching and hackling, prior to impregnation. All laboratories used the production process as outlined above except one, HSB, which used pultrusion to produce the samples. Figure 4 shows the fibre stiffness and strength for the different laboratories.

Both for E_{f1} and E_{f2} no statistical differences could be found. Back-calculated strength values are more prone to variation as is clear from the figure. This is to be expected as the strength of a composite material is highly sensitive to defects that can be caused by the production process. Lower strengths were reported when consolidation pressure was low. Lower pressure during consolidation encourages heterogeneous fibre distribution and porosity formation which may lower strength.

From the tests that were performed a mean value could be determined of 59.8 ± 2.4 GPa for E_{f1}, 40.8 ± 3.5 GPa for E_{f2} and 527 ± 138 MPa for the fibre strength. E_{f1} is the "real" Young's modulus of the material (by definition, the Young's modulus should be measured at very low strain values). Moreover, because in most practical applications, the mechanical response at low strains is predominant, E_{f1} is the stiffness value that should be used in structural calculations. However, it is advised that E_{f2} should be be reported as well for flax fibres.

The standard deviation on the stiffness and strength values, measured with the IFBT-test, is low and even comparable to the variation found on E-glass fibres. The standard deviation on the stiffness is 5.5 times lower than that measured using single fibre tests. Similarly, for strength the spread on the results was reduced by a factor 2.3. It is therefore incorrect to state that flax fibre properties are highly variable, at least within the same batch of fibres. Flax fibre stiffness and strength can reliably and accurately be determined by applying the IFBT method.

The impregnated fibre bundle test (IFBT) is the preferred method to accurately determine the mechanical properties of flax and hemp fibres for composites. A detailed methodology to perform the test was created by the European Scientific Council of CELC which can be found on www.europeanflax.com accompanied by video material which describes the sample production.



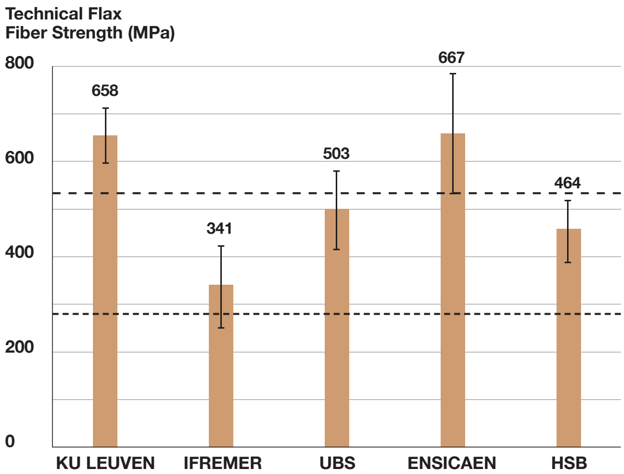
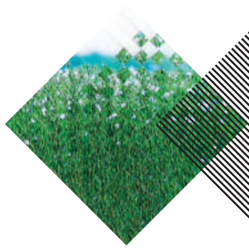


FIG. 4 **Back-calculated fibre stiffness and strength from the IFBT samples for the five different laboratories. Horizontal lines indicate the average values when all samples from all laboratories are considered. [2]**

In conclusion the IFBT is the preferred method to evaluate the composite performance of flax and hemp fibres because:

- It can determine the stiffness and strength of the fibres with very high accuracy and low standard deviation. The standard deviation on the mechanical properties is comparable to synthetic fibres.
- It reflects the properties of the fibres as they behave in the composite, opposed to single fibre tests
- The method can be extended to other (quasi)-unidirectional configurations such as yarns, rovings or quasi-UD weaves.
- The method is fully accepted and worldwide used by the composites community & industry for synthetic fibres for composites.
- The tests require much less time than performing (a statistically relevant number of) single fibre tests.



4.4 Applicability of the method – a case study

Since the method was published, it has proven its use in several situations where fibre quality or performance needed to be examined. As an example, the effect of the retting degree on the fibre stiffness and strength of flax fibres (Vesta variety) has been evaluated, using the IFBT-method. The growing and extraction of the fibres are indeed subjected to several variables that cannot always be controlled. The important question is then whether or not these variations have a significant effect on the fibre properties, relevant for composite applications *(and hence measured using the IFBT-method)*. A more detailed discussion on these variables and other effects is provided in chapter 7 of this book.

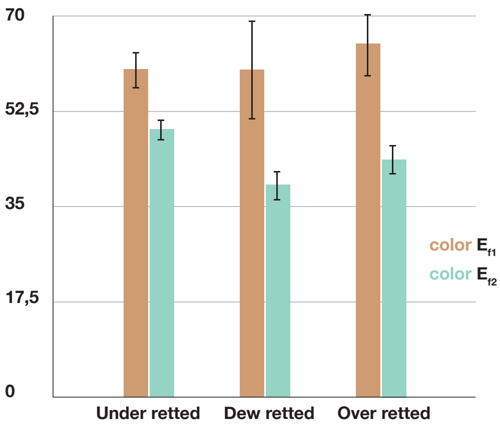
Variation of composite performance with retting degree

Retting is a process that employs micro-organisms to degrade part of the flax stems on the field. It is required to extract the fibres from the stems during subsequent mechanical operations. The extent or degree of retting is difficult to control since it depends on the amount of rainfall during the process. Flax fibres of the same variety but with different extents or degrees of retting were examined using the IFBT method. The dew retted fibres were considered to receive the correct amount of rainfall for optimal processing in scutching and hackling. Under and over retted stems were respectively, degraded too little and too much thereby decreasing the long fibre yield during further extraction. To obtain unidirectional bundles, the fibres were scutched.

Figure 5 shows the results for fibre stiffness and strength, as measured using the IFBT method, for the different retting degrees. The initial fibre modulus, E_{f1}, is not affected by the difference in retting. This result is important as it is one of the key parameters in the design of structural components. It shows that limited variation in retting degree does not necessarily mean that the resulting composites have different stiffness. E_{f2} appears to decrease with the extent of retting but this should be confirmed by additional data. Moreover, it is a design parameter that is of secondary importance. Strength of the fibres increases with increased retting degree. This could be due to the more efficient removal of shive particles when the stems are retted more. Shives can act as stress concentrators in the composite which lower the strength.

The presented data oppose the “myth” that flax fibres have highly variable properties because they are influenced by growing conditions, extraction methods, etc. This belief originates from the year long experience in producing flax fibres for textile applications (where the fibre undergoes further processing steps like hackling, carding, spinning, weaving..). For composite applications however, we should look at the behavior of the flax fibres when they are embedded in a matrix, and not at the non-embedded fibres, as is done in single fibre tests or in dry bundle tests. Although there is some variability, it is not as severe as currently believed, and it should be assessed quantitatively by using a fibre test method which is specifically developed for composite applications, namely the IFBT method .

Technical Flax Fibres Modulus (GPa)



Technical Flax Fibres Strength (MPa)

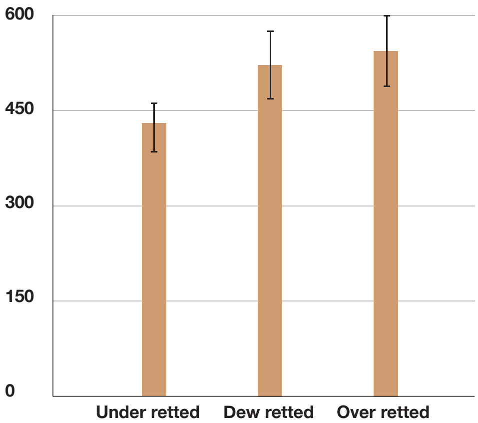


FIG. 5 **Back-calculated fibre stiffness and strength from the IFBT samples for the different retting degrees.** (Source: PhD Kevin Hendrickx)

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V

Is the Reproducibility of Flax Fiber Properties Really an Issue?

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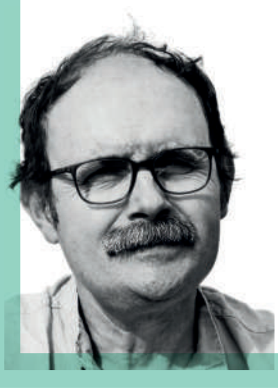

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1. Introduction

The quality of the plant fibers used to reinforce polymer matrices is often considered to be scattered. The scattering of the mechanical properties is presumed to be influenced by weather conditions, among other things, and it is often put forward as a limitation for the use of plant fibers as reinforcement in structural composite materials. This assertion is questionable, and it is of interest to analyze the different checks at each stage of the fiber production process, the origin of the fiber properties, and all parameters that could affect their mechanical properties.

Moreover, we note that synthetic fibers used as reinforcement (e.g. glass or carbon) also display scattered mechanical properties (Coroller et al., 2013), and that the textile industry has been making industrial use of them for a very long time.

The flax and hemp value chain is organized from upstream to downstream, and is based on expertise and techniques that are specific to the processing of the plant: varietal selection, dedicated harvesting machines, mechanical processes to convert the plant into fiber.

The value chain is structured to address demand from the markets.

2. The high mechanical properties for flax fiber do not occur by accident

Flax is a dicotyledon from the Linaceae family. Of the 298 linum species (Montaigne, 1997), the annual plant *linum usitatissimum L.* is the one that is cultivated on the largest scale. It produces fibers (Figure 1) and oleaginous seeds. If the production is geared towards the fiber mechanical properties, the term used is “fiber flax”; if not, it is “linseed flax”. The varietal selection and mode of cultivation (number of plants per square meter, plant maturity at harvest, the type of farm machinery used, etc.) change as a function of the crop’s main end purpose (fibers or seeds). Note that linseed flax also produces quality fibers (Pillin et al., 2011) that are used to make paper, for example.

FIG. 1 **Flax fibers.**

The flax fibers are located around the stalk periphery in the form of a ring (Müssig & Hughes, 2012). They serve as mechanical support for the plant, which is very tall and slender. The remarkable properties of these fibers (average length of the elementary fiber is about 25 mm for an average diameter of 15 micrometers, with good mechanical properties) can be explained by the initial intrusive development of a cell (Snegireva et al., 2010), followed by a filling stage (Rihouey, Paynel, Gorshkova, & Morvan, 2017). As the walls thicken, cellulose fibrils are laid down in a spiral at a roughly 10° angle with respect to the stalk axis. There is a high proportion of these fibrils (more than 65% by weight), largely determining the fiber mechanical properties. So, the good properties of flax fibers can be explained by their function in the plant and related to the plant's gene pool.

3. Controlling the different flax-fiber production stages

Crop rotation

Recommendations on cultivation practices are available to farmers in the literature (Bert, 2013). Several different plants are grown on a farm, including flax, which is included in crop rotation schemes; this means that the same plot is sown with flax about every seven years. In this way, flax serves as a break crop, helping to minimize diseases and pests that remain in the soil and to break the cycle of certain weeds.

Selecting the variety for a given terroir

Varietal selection is permanent and the variety is chosen based on the specific terroir. In France, for example, each new variety is registered in the official catalogue of species and varieties. Strict rules apply for this; e.g., the variety must be different from the varieties already registered; it must be homogeneous and stable, i.e. maintain its characteristics from generation to generation; and it must have sufficient agricultural, technological and environmental value. The main criteria used by the selector are fiber yield, resistance to disease, and lodging stability. The intellectual property rights (and therefore protection) for a new variety on the market are guaranteed for a period of 20 years. Therefore, the varieties cultivated inevitably change over time.

The number of plants per square meter

The use of **certified seed** provides a number of guarantees (germinative ability higher than 92%, clean and healthy plants), so shoot emergence losses are minimized these days. Farmers now also have access to specific seed distributors. A planting rate of 1,500 to 1,900 seeds per square meter is recommended in order to obtain from **1,500 to 1,600 viable plants per**

square meter (Bert, 2013) (Figure 2). This parameter influences the stalk morphology (height and diameter), the lodging resistance, and also the mechanical properties of the elementary fibers (Bourmaud, Gibaud, & Baley, 2016). For more than about 2,000 plants per square meter, both the fiber mechanical properties and the plant's lodging resistance decrease.

FIG. 2 **Flax plants** © S.Randé/CELC.

Monitoring plant growth

The life of a plant generally goes through five phases: germination, growth, flowering, seed formation and senescence. It develops over a well-defined period (100 days for flax), in weather conditions that change in terms of temperature (flax grows above 5°C, or 41°F), rainfall, sunlight and day length. Unlike bast plants for textiles, fiber flax is harvested when the fibers are mature. To determine this stage, the daily temperature is measured. Above 5°C, the rate of development for flax is directly proportional to the sum of temperatures received by the plants since seeding, a benchmark that is easy to memorize. The criterion used is the sum of temperatures (ST), expressed as follows:

$$ST = \sum_{i=1}^{n} \left(\left(\frac{T_{maxi} + T_{min}}{2} \right) - 5 \right)$$

where n is the number of days, Tmaxi is the maximum daily temperature and Tmin is the minimum temperature. Fiber maturity is obtained for an ST ranging from 950 to 1,100°C (or 1,742 to 2,012°F) (Bert, 2013). The value of ST is known for each stage of the plant's development: ST = 50°C shoot emergence, ST= 550°C flowering, ST= 650°C capsules formed, ST= 950-1,100°C fiber maturity. Above 950°C, the fiber content ceases to increase, whatever the growing conditions and variety (Bert, 2013). Seed maturity is obtained for ST = 1,150°C. Above 1,100°C, the flax plants are overmature, and start to turn into ligneous compounds that encrust the fibers. The presence of lignins in abundance complicates fiber retting and the mechanical extraction processes (scutching and hackling). Therefore, it is important to monitor plant maturity to avoid lignification of the walls. **Such monitoring is the first step in controlling the fiber properties in terms of stabilizing the values over the years of cultivation.**

Harvesting

Fiber quality depends not only on the cultivation system and the plant development conditions, but also on the harvesting process. The harvesting steps, which include pulling, retting, turning, and rolling up, are organized in order to preserve the fiber properties. Specialized machines are used to pull out the flax stalks, which are then carefully laid on the ground in swathes before retting (Figure 3). During the retting process, microorganisms (fungi and bacteria) attack the stalks, damaging the links between the fibers in the bundles and between the fibers and other tissues. To achieve homogeneous retting, the stalks have to be turned. The extent of retting is controlled on each plot through sampling. Humans have utilized retting for textile applications for a very long time – it is one of the first biotechnologies ever used. This step is also necessary to develop the fibers for composite applications, as retting enhances the fiber mechanical properties (Martin, Mouret, Davies, & Baley, 2013).

FIG. 3 **Flax plants during retting** © S.Randé/CELC.

The swathes are then carefully rolled up to keep the stalks parallel, with all the heads at the same end. For proper conservation, the moisture content of the stalks should not exceed 16% during rolling. Flax strings are used to secure the bales of flax to avoid any source of pollution, e.g. from synthetic fibers. The bales are stored in a sheltered location that is protected from moisture uptake (concrete floor)

Mechanical fiber extraction

The first process used is scutching, which consists of extracting the fibers from the stalks by crushing and beating the straw to eliminate the epidermis, the shives (lignified core material), and dust particles. Scutching is done on specialized machines with settings that can be adapted for each batch. This mechanical operation generates short fibers (individual bundles of shorter lengths). The term for the material of quality used for textiles is scutched fiber. This consists of fiber bundle assemblies that are approximately as long as the plant itself, with heads and bases identified and carefully aligned. At the end of the scutching line, operators sort the bundles to obtain homogeneous fiber batches (Figure 4). The flax is packaged into round bales of about 100 kg each (Figure 5). In addition, a hackling operation is sometimes performed to refine and divide the bundles. Each batch of fibers is assessed by its color, tenacity, fineness, and the length of the elementary fibers (Bert, 2013).

FIG. 4 **End of a scutching line with fiber bundle inspection** © S.Randé/CELC.

FIG. 5 **Storage of scutched fibers** © S.Randé/CELC.

Conclusion

The properties of flax fiber justify their use as reinforcement for polymer-matrix composites. Their high properties are not accidental, but can be explained by their function within the plant (supporting tissue for a tall and slender plant), their gene pool, and the way they develop. For many years, fiber production has been carried out by farmers and scutchers working together to produce a high-quality fibrous biomass. For that, the cultivation and harvesting practices have been well-identified and monitored at all stages. The existence of a European supply chain is an advantage for guaranteeing traceability and development. A number of scientific studies have been led in order to develop characterization tools and to understand the influence of certain parameters on the mechanical properties of elementary flax fibers and fiber bundles.

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Coroller, G., Lefeuvre, A., Le Duigou, A., Bourmaud, A., Ausias, G., Gaudry, T., & Baley, C. (2013). Effect of flax fibres individualisation on tensile failure of flax/epoxy unidirectional composite. Composites Part A: Applied Science and Manufacturing, 51. http://doi.org/10.1016/j.compositesa.2013.03.018

Martin, N., Mouret, N., Davies, P., & Baley, C. (2013). Influence of the degree of retting of flax fibers on the tensile properties of single fibers and short fiber/polypropylene composites. Industrial Crops and Products, 49. http://doi.org/10.1016/j.indcrop.2013.06.012

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VI

Added Value for Your Product

The adoption of natural fiber reinforcements for composites can provide significant added value, thanks to the unique properties of these materials. In addition to reduced environmental impact (to be discussed in Chapter 8), the **remarkable properties** of flax reinforced composites include:

Vibrational damping / Impact response / Fatigue behavior Moisture sensitivity / Biodegradability / Acoustic properties Radiowave transparency / Hybridization / Recyclability.

1. Vibrational damping

One advantage of natural fiber composites, observed particularly in dynamic applications, is their intrinsic damping capacity. There are various ways of measuring damping properties. One of the more common is to use dynamic mechanical analysis (DMA) to determine a loss factor, in which the loss modulus is divided by the storage modulus (sometimes referred to as tan δ). The higher the loss factor, the better the material damping. Some recent studies have quantified these effects and shown significantly better damping properties for flax fiber composites than for equivalent glass-reinforced materials. **For example, UD flax fiber reinforced epoxy composites have an approximately 100% higher loss factor than glass fiber and carbon fiber reinforced epoxy [Duc 2014]**, see Figure 1 below.

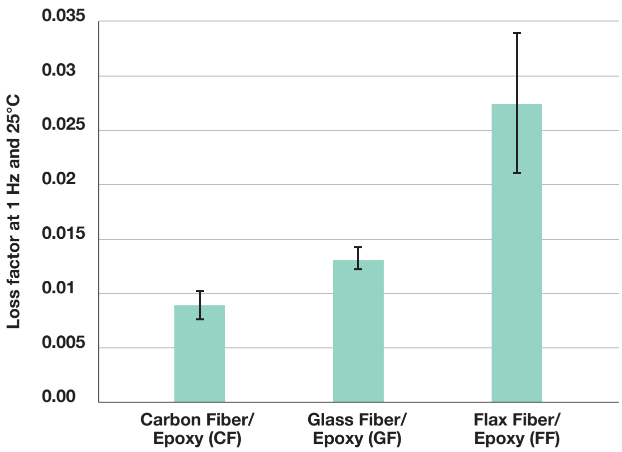

FIG. 1 **Loss factors for composites with different reinforcements.**
(From Du et al, 2014)

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Others have also added flax to carbon fibers and shown a similarly strong influence on damping. This damping improvement could be beneficial for noise and vibration reduction in transport applications.

More details can be found in:
Duc et al., Composites Part A (2014), 64, pp. 115-123
Prabhakaran et al., Procedia Engineering (2014), 97, pp. 573-581
Assarar et al., Composite Structures (2015), 132, pp. 148-154

2. Fatigue behavior

There is still relatively little data on the fatigue performance of natural fiber composites. A comparison study by Shah et al. [2013] indicated that although the absolute fatigue performance of glass fiber composites is far superior to that of plant fiber reinforced materials, it is interesting to note that fatigue strength degradation rates are lower in plant fiber composites than in GFRP, see Figure 2 below.

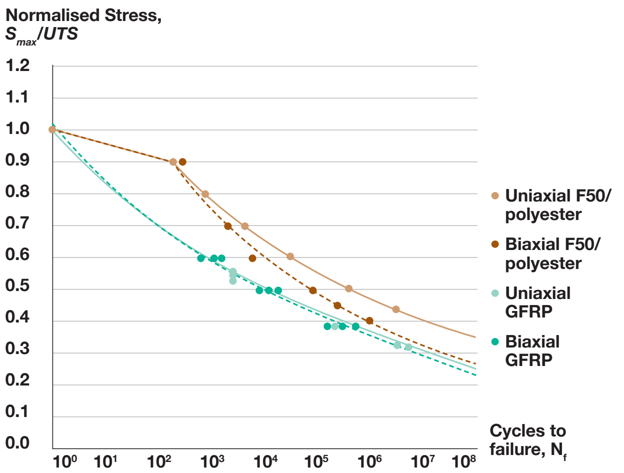

FIG. 2 **Fatigue plots, Shah et al. 2013. "F50" is 28% fiber content by volume flax. "Biaxial" is +/-45°**

Liang et al. [2012] found a similar result. Thus, once a structure has been dimensioned for static strength, the property loss after fatigue loading may be lower for flax composites compared to glass fiber materials.

Bensadoun et al. [2016a] have extended these studies to different types of flax reinforcements (weaves, biaxial non-crimp and UD). The results showed that the various textile architectures have different static behavior, but do not necessarily influence the fatigue life at lower stress levels. Furthermore, the full S-N curves have shown no clear difference between the woven fabric and cross-ply laminates. The UD composites, tested in the fiber direction, show a higher normalized SN-curve, whereas the random mats show a lower one. Further studies [Bensadoun, 2016b] confirmed Shah's results, namely that in terms of normalized stress (applied stress divided by density) flax and glass fiber composites with similar reinforcement architectures behave very similarly.

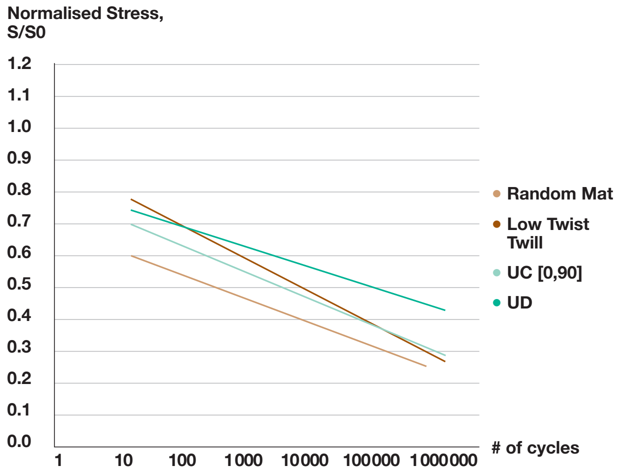

FIG. 3 **Normalized fatigue data trendlines for four flax-epoxy composites (Vf=40%, except for random mats = 30%) at R = 0.1 (normalized to the static strength).**

Shah et al., Composites Science and Technology (2013), 74, pp. 139–14
Liang et al., Composites Science and Technology (2012), 72, pp. 535–543
Bensadoun et al., Composites part A (2016), 82, pp. 253-266
Bensadoun, PhD thesis University of Leuven, Belgium (2016)

3. Impact response

Impact resistance is a structural rather than a material property, and it is difficult to compare materials with different stiffnesses. There are many material parameters that affect impact performance (see figure below), including the impactor's mass and drop heights, which determine the impact energy, but also the impactor shape and the support conditions.
Bensadoun et al. [2017] performed non-penetrating and penetrating impact tests on flax composites with different reinforcement architectures (random mats, weaves, biaxial non-crimp). They found that the damage (and therefore the amount of energy absorbed during impact) is dominated by fiber fracture, and not by delamination development, as is the case in glass and carbon fiber composites. However, the matrix choice also has an important effect on the impact performance, with flax reinforced PP showing a better energy absorption than flax reinforced epoxy composites. The absorbed energy at perforation for the flax-PP composite was more than 50% higher compared to the flax-epoxy materials. Moreover, it was found that the flexural strength after impact for a non-penetrating impact of 3.1 J on a 2mm thick plate is only slightly lower than the flexural strength before impact

(see Figure 4 below). Overall, the type of architecture was found to have a limited effect on the absorbed energy at perforation.

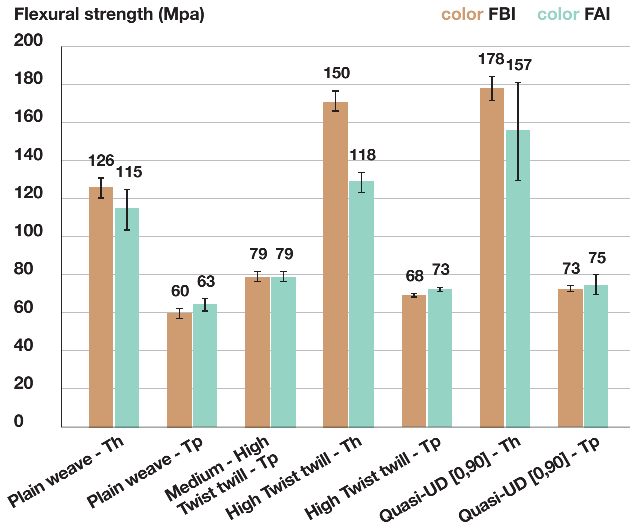

FIG. 4 **Flexural strength before and after impact (for a non-penetrating impact of 3.1 J on a 2mm thick plate) for flax composites with a thermoplastic matrix (Tp) or a thermoset matrix (Ts).**

Another example of a comparison between residual strengths in bending relates to sandwich materials after low energy impacts, and is shown below. This suggests that flax reinforced facings on cork cores are less sensitive to impact than a sandwich of the same geometry with glass fiber facings on PVC foam core. However, if another configuration is studied, this may no longer be the case. It is recommended that tests be performed on structures that are representative of the geometry and boundary conditions of the end application.

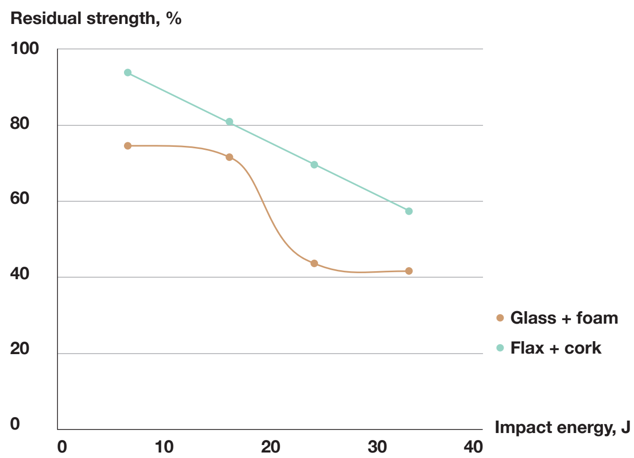

FIG. 5 **Drop weight impact test on flax/polyester panel, experimental set-up and example of residual strengths after impact for sandwich materials, Ifremer results**

Park et al. [2018] recently performed an impact analysis of an automobile hood structure according to European Pedestrian Protection regulations, and showed that flax reinforced vinylester could replace steel for that application.

More work is needed to understand the impact response of plant fiber composites.

Park et al., Composite Structures (2018), 184, pp. 800–806
Bensadoun et al., Composite Structures (2017), 176, pp. 933–944

4. Moisture sensitivity

Sensitivity to moisture is often cited as a major disadvantage of natural fiber composites, but the water ingress is dominated by the matrix resin. Thus the use of flax fibers in boat structures is not prohibited, provided the choice of matrix resin is appropriate. This has been shown in some recent applications, in which flax fibers were impregnated with polyester resin for a 7-meter multihull [Bosser 2013], and with epoxy resin for a 4.6-meter monohull [Castegnaro 2017]. These have been at sea for several years now without problems (see figure below).

Trimaran Gwalaz at sea © IFREMER/Kairos.

Bosser et al., JEC magazine (2013), 84, pp. 45-46.
Castegnaro et al., Ocean Engineering (2017), 133, pp. 142–150

More generally, the effect of moisture on flax composite properties appears to be less severe than initially feared. A recent study [Berges et al., 2016] showed that water vapor sorption certainly induces a significant change in the shape of the tensile stress-strain curve, with a decrease in the dynamic elastic modulus of about 20%. However, contrary to all expectations, water saturation does not degrade the monotonic tensile strength of such a flax-epoxy composite, and even leads to an increase in the fatigue strength for a high number of cycles. It also leads to a 50% increase in the damping ratio.

Berges et al., Composites Part A (2016), 88, pp. 165–177

Figure 6 shows an example of the effect of water immersion for the flax/polyester material used in the Gwalaz trimaran. A set of samples was removed from the sandwich materials of the float after 18 months' navigation. Half were tested as received, and very little water was found in these materials. The remaining samples were then fully saturated with seawater and retested. Once again, as noted by Berges et al. [2016], a drop in tensile modulus is noted along with an increase in failure strain, but strength remains constant.

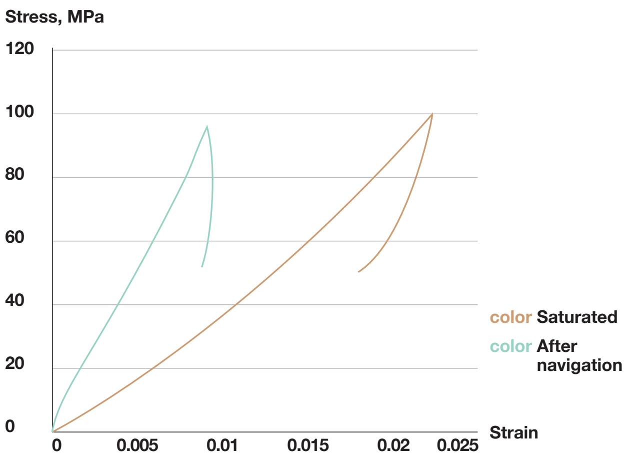

FIG. 6 **Influence of water on flax/polyester.**

The sensitivity of natural fibers to water can also be put to use in bio-inspired mechanisms. For example, Le Duigou et al. [2017] proposed a flax/PP laminate as a moisture sensitive actuator. Hygromorph biocomposites (HBCs) are hygroscopically active materials with morphing ability upon a moisture variation. They turn the water sensitivity of natural fibers into the driving force of the HBC actuation. A novel asymmetric 0/90° microstructure, where both passive and active layers include flax fibers, has been used.

Le Duigou et al., Industrial Crops and Products (2017), 99, pp. 142-149

5. Biodegradability

Whereas fiber length in wood is in the order of some mm, other natural fibers provide longer technical fibers that are more suitable for reinforcing composite materials. Because of the chemical similarity of natural fiber composites with wood products, more attention has recently been focused on parameters linked to moisture behavior, biological durability and end-of-life processing. Moisture dynamics is key in the protection mechanisms against decay but also implies limited use in ground contact. The existing standard to assess wood decay for wood-based panels could be adapted by including a pre-treatment that brings wood plastic composites (WPC) to a high moisture level at the start of the fungal test [Defoirdt et al., 2010], later confirmed as part of testing of natural fiber composites (NFC) [Defoirdt et al., 2017].

For natural fiber composites in structural and load-bearing applications, long reinforcing fibers are required. Therefore, much research is performed on flax fiber reinforced composites to optimize them for high performance use. In most cases, such research focuses on the mechanical properties, yet the assessment of moisture behavior, dimensional stability and biological durability is also an important aspect concerning in-service performance. Defoirdt et al. (2017) assessed these properties of flax composites made with maleic anhydride grafted polypropylene (MAPP) or epoxy and reinforced with mat, unidirectional, cross-ply unidirectional, quasi unidirectional, plain weave or twill weave reinforcements. Testing water immersion and fungal resistance with *Coniophora puteana* and *Trametes versicolor* showed that epoxy composites performed better than MAPP composites. Furthermore, less water absorption and lower biological degradation was observed when reinforcement was more structured. Composites with moisture content below 26% were hardly decayed. Although 14 days of immersion at 70°C was sufficient to moisten WPCs enough for fungal degradation (Defoirdt et al., 2010), the immersion period seems to be too short for the flax composites. **The low, slow moisture uptake by natural fiber composites must be seen as a strong protection to prevent fungal decay.** In general, decay resistance of wood products and related lignocellulosic materials is now based not only on the intrinsic or enhanced durability due to presence of components active against decay, but also on the moisture dynamics, which are taken into account as critical in an overall service life performance assessment.

FIG. 7 **Basisiomycetes decay test showing differences in fungal resistance of flax fiber composites.**

Defoirdt et al., International Biodeterioration & Biodegradation (2010), 64, pp. 65-72
Defoirdt et al., Proceedings IRG Annual Meeting (ISSN 2000-8953) (2017), doc. IRG/WP 17-40803, 15p.

Biodegradability of natural fibers can be considered positive, as it can be used to obtain a more sustainable life cycle analysis appraisal for composites. In this respect, some research is also focusing on fully biodegradable natural fiber composites that are based on renewable resources. Du et al. [2014] fabricated polymer composites with poly(lactic acid) (PLA) and cellulosic natural fibers (hardwood and softwood high-yield pulp, and bleached kraft softwood pulp fibers) by combining the wet-laid fiber sheet forming method with the film stacking composite-making process. The incorporation of pulp fibers significantly increased the composite storage moduli and elasticity, promoted the cold crystallization and recrystallization of PLA, and dramatically improved composite tensile moduli and strengths.

Du et al., Composites Part B: Engineering (2014), 56, pp. 717-723

Zhang et al. [2005] used plasticized China fir sawdust as matrix for both discontinuous and continuous sisal fibers to produce composites from renewable resources. For continuous (unidirectional) sisal reinforced composites, the strength reaches maxima at a sisal content of 30 vol% with approx. a flexural strength of 160 MPa and tensile strength of 90 MPa, while the moduli increased at a 30 vol% sisal content with indicative flexural modulus 12 GPa and Young's modulus 15 GPa. Therefore, these all-plant fiber composites combine moderate mechanical properties with full biodegradability, and could serve as an alternative to petro-based materials in terms of structural applications.

Zhang et al., Composites Science and Technology (2005), 65, pp. 2514-2525

Bayerl et al. [2014] investigated the influence of flax fiber reinforcements on the decaying process of poly(lactic acid) (PLA) in flax/PLA composites under composting conditions. The results indicate that the fibers enhance the biodegradation by enlarging the potential surface that contributes to the decaying process. At the same time, the fibers act as channels, distributing water and microorganisms in the composite. The decaying process is attributed to fiber decomposition and hydrolysis of PLA, which leads to increased degradation rates for composites with high fiber weight content.

Bayerl et al., International Biodeterioration & Biodegradation (2014), 96, pp. 18-25

6. Acoustic properties

Natural fiber based composites are becoming attractive candidates for use in various applications owing to their mechanical and sound-absorption properties. However, studies have been dedicated to understanding their mechanical properties, and few focus on quantifying their sound attenuation behavior. A noteworthy result presented by Lee et al. [2017] was that the noise reduction coefficient increased from an average value of 0.095 for glass fiber epoxy composites to 0.11 for unidirectional flax/epoxy composite, and to 0.10 for cross-ply flax/epoxy system. This suggests that flax fibers are indeed better sound absorbers than glass fibers, and in general that flax/epoxy composites could be viable, less expensive, and ecologically superior substitutes for glass-fiber based composites, particularly in applications where sound absorption is important.

Lee et al., Journal of Natural Fibers (2017), 14, pp. 71-77

Buksnowitz et al. [2010] characterized the acoustical behavior of natural fiber composites. Regenerated cellulose fibers (Lyocell), hemp fibers, and flax fibers were embedded in an epoxy matrix. These unidirectional composites were tested for their logarithmic damping decrement, the resonance frequency, the ultrasound velocity, the dynamic and static modulus of elasticity, and bending strength and density. Glass-epoxy composites served as a reference. All tested natural fiber composites showed a significantly higher damping at lower densities. The ultrasound velocity was in the range of the reference for Lyocell- and hemp-fiber composites. The specific acoustical properties of these natural fiber composites appear to be particularly suitable for high-value applications, e.g., devices that require high damping of the body structures.

Busknowitz et al., Journal of Reinforced Plastics and Composites (2010), 29, pp. 3149–3154

In addition, it is also possible to industrially manufacture acoustic screens for the automotive industry with PP/flax [Merotte et al, 2017].

Merotte et al, Polymer Testing 51 (2016), 51, 174–180

7. Radiowave transparency

A radome is the protective part covering an antenna that transmits or receives electromagnetic waves. Its purpose is to preserve the antenna from damage due to various environmental conditions (temperature, hail, rain, sand, etc.). At low frequencies (f < 10 kHz), the flax fibers' cellulosic structure offers a low relative dielectric permittivity associated with moderate dielectric loss, which gives it excellent electrical insulation properties. At high frequencies, the dielectric constant measured for the flax fiber reinforced biocomposites is stable between 1 to 6 GHz. **Compared to the same structure manufactured using glass fibers [Duriatti & Callebert, 2015], the results show that flax reinforcements allow the signal to pass through the radome with a nearly 10% higher velocity, while minimizing its attenuation,** see Figure 8 below.

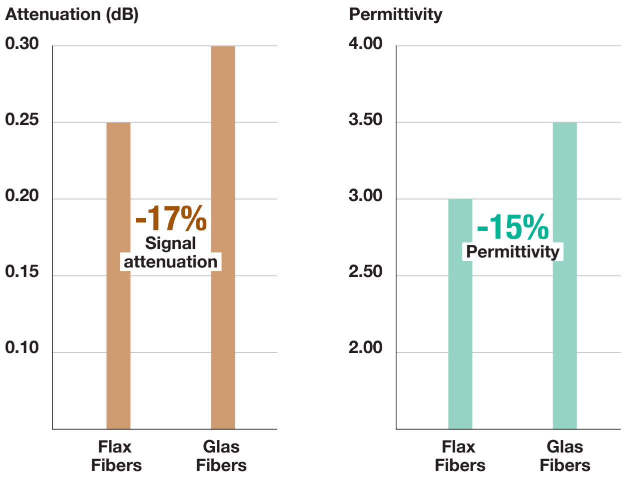

FIG. 8 **Transparency efficiency of flax-reinforced composites.**

Duriatti and Callebert, JEC Technical Posters (2015)

8. Hybridization

Natural and synthetic fibers are being used more and more as reinforcements in various applications. While the latter are popular for their generally superior mechanical properties, natural fibers are eco-friendly and cheap, and they have good vibro-acoustic properties [Kureemun et al., 2018]. In this study, the performance enhancement of natural fiber reinforced composites through hybridization with carbon fibers was benchmarked against flax (woven, at 30% fiber volume fraction). With 8% of carbon by volume, a more than 50% increase in strength and stiffness is achievable, with a specific strength 30% higher than aluminum. An additional 6% increase in the carbon volume fraction renders the composite more than 2.3 times stronger and stiffer than flax epoxy.

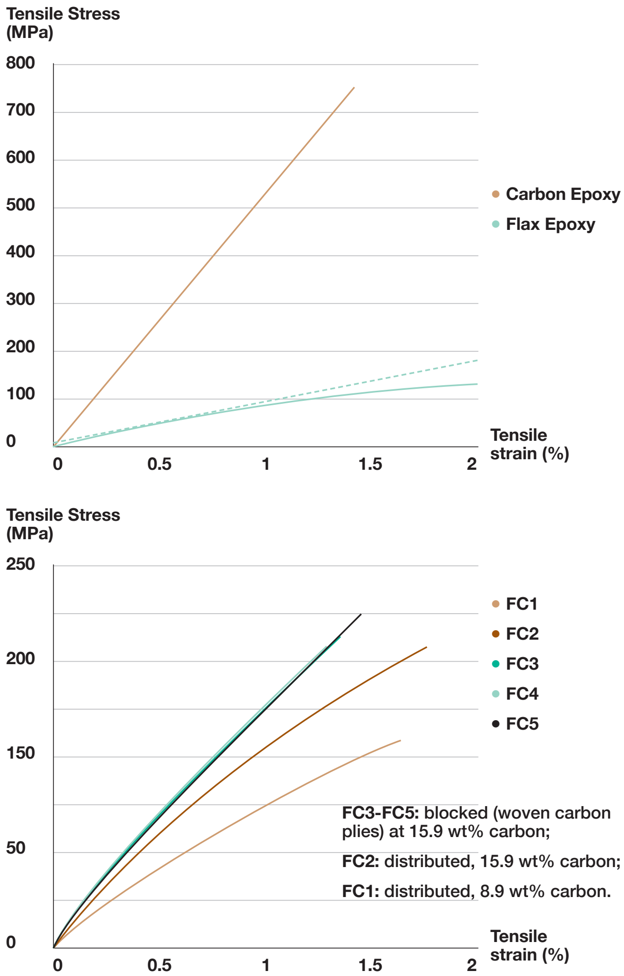

FIG. 9 **Stress-strain characteristics of (a) non-hybrid flax and carbon epoxy, (b) hybrid laminates FC1-FC5 under tension.**

Kureemun et al., Composites Part B 134 (2018), pp. 28-38

Dhakal et al. [2013] produced unidirectional (UD) and cross-ply (CP) cellulosic flax fiber/epoxy composites and produced hybrids by adding UD carbon fiber prepreg onto flax composites. A compression molding technique was used to produce both flax and carbon/flax hybridized laminates. The experimental suggest that cellulosic flax fiber reinforcement contributed to improve the toughness properties by promoting energy absorption by multiple crack propagation. The thermal stability, water absorption behavior, and tensile and flexural properties of the hybrid composites are significantly improved in comparison with UD and CP flax composites without hybridization. The hybridization of carbon fiber provides a much stiffer (tensile modulus of Flax UD 2.9 GPa and FlaxCP–Carbon 11.9 GPa) and stronger (tensile strength of Flax UD 126.3 MPa and FlaxCP–Carbon 284.8 MPa) material than the hybrid's natural fiber counterparts.

Dhakal et al., Carbohydrate Polymers (2013), 96, pp. 1-8

9. Recyclability

The manufacturing of plant fiber reinforced composites is a growing sector for many environmental reasons. The production of vegetal fibers requires lower energy than for synthetic fibers; moreover, they have a low density, making it possible to reduce the transport costs, and they offer several end-of-life options (combustion, recycling or composting ith a biodegradable matrix) [Le Duigou et al., 2008]. Polypropylene/hemp fiber composites exhibit interesting recyclability [Bourmaud and Baley, 2007]. The evolution of the mechanical properties as a function of the number of processing cycles (Figure 10) demonstrates that the tensile strength of the polypropylene-hemp fiber composite remains stable, unlike those of the polypropylene-glass fiber composite.

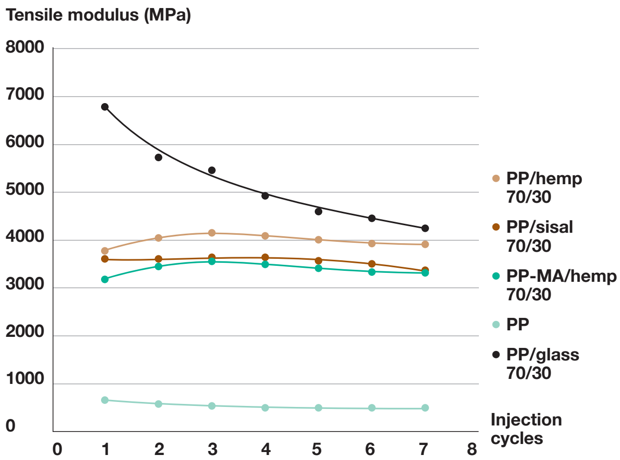

FIG. 10 **Evolution of tensile modulus with number of cycles.**

The stable mechanical properties of composite materials reinforced with hemp fibers could be due to the limited evolution of the aspect ratio over the number of cycles (Figure 11).

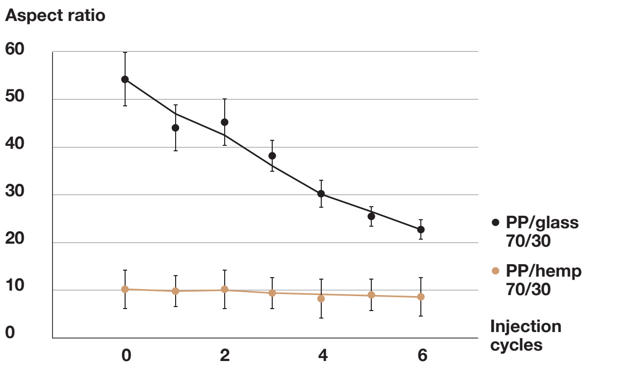

FIG. 11 **Evolution of fiber aspect ratio with number of recycling cycles.**

Bourmaud and Baley, Polymer Degradation and Stability (2007), 92, pp. 1034-1045

Le Duigou et al., Composites Part A: Applied Science and Manufacturing (2008), 39, pp. 1471-1478

VII

Composite Manufacturing Processes and Applications on the Market: a Combination of Knowhow, from Producers to Manufacturers, to Finished Product

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This chapter focuses on the complete process chain for the production of natural fiber composites (NFCs), from raw and semi-finished materials down to the processing possibilities. In the second part, some applications for different end-use markets are described in more detail.

1. NFC Processing Technologies

The way natural fibers are introduced as reinforcing material in polymer composites has to be adapted to the available production techniques. These techniques are developed in ways similar to those developed for advanced synthetic fiber composites over the past decades. Figure 1 shows the more commonly used techniques for producing natural-fiber polymer composites these days. The classification in Figure 1 is based on polymer type (thermoplastic or thermoset), the post-process status of the products (semi-finished or finished) and the post-processing fiber geometry.

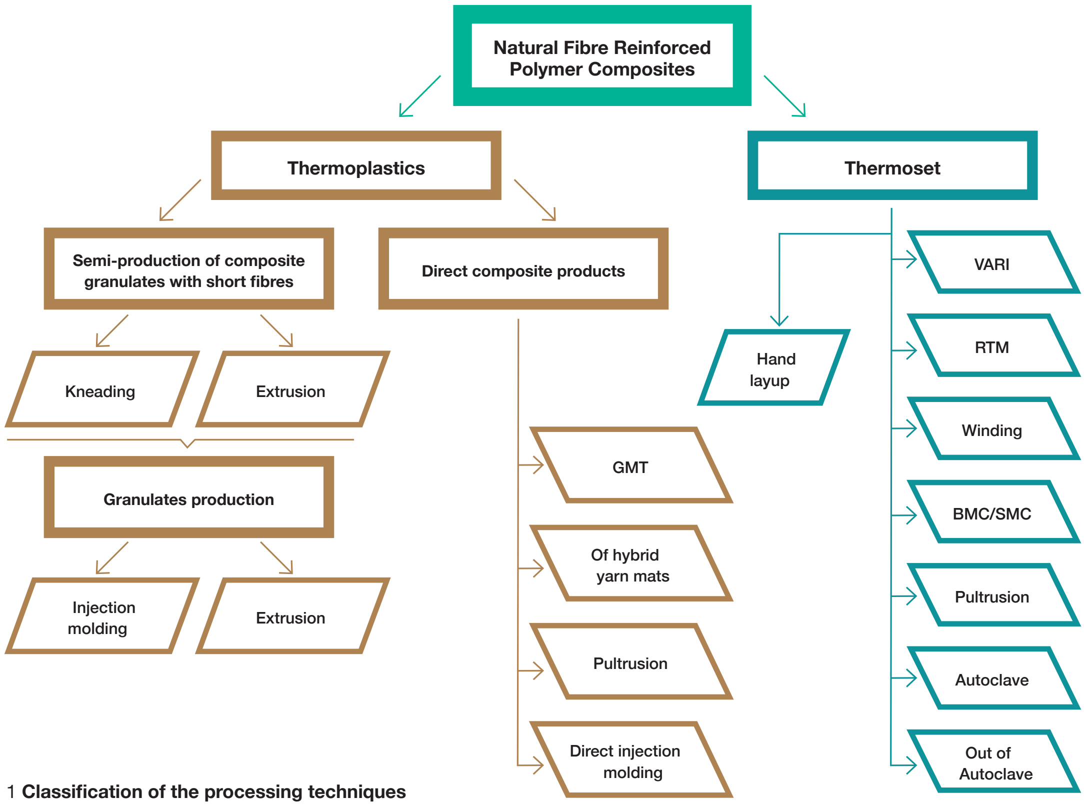

FIG. 1 **Classification of the processing techniques for natural fiber polymer composites.**

Selection of the material combination and the production technique depends on both the required properties of the structure and the desired production rate. However, attention should be paid to the choice of processing parameters; due to the limited processing window for NFC, these should be carefully selected. Natural fibers degrade quickly at excessive processing temperature.
Selection of the material combination is related to the choice of matrix and to the different types of natural-fiber textile structure.

→*Thermoplastic matrix systems*

Thermoplastic matrix systems are created as linear molecule chains with high molecular mass. Due the nature of the linear or branched molecules, the polymer can be heated up to the high viscous melting phase and stiffen again when cooled. A rapid cycle of repeated heating and cooling enables the material to be processed quite fast, as no chemical reaction is necessary to create the structure. An additional advantage is that the material is recyclable.

→*Thermoset matrix systems*

Thermoset matrices are based on molecules that crosslink during the curing step to create three-dimensional molecular structures, which cannot transform back to the liquid phase again after curing. This type of matrix offers low viscosity before curing, which enables the material to impregnate fibers very fast. Thermoset matrices also have excellent post-cure properties, especially for creep and fatigue loading.
The chemical curing cycle is longer than the one for thermoplastics, so the process also takes longer. This limits the use of thermosets in large series production.

Thermoplastic composites

Today there are a number of different processes/process chains to produce natural fiber thermoplastic composites (NFTC), from the raw fiber down to the final product.

ADVANTAGES

- **Lower specific weight**
- **Recycling is possible**
- **Cleaner processing**
- **Unlimited storage time of semi-finished products (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**

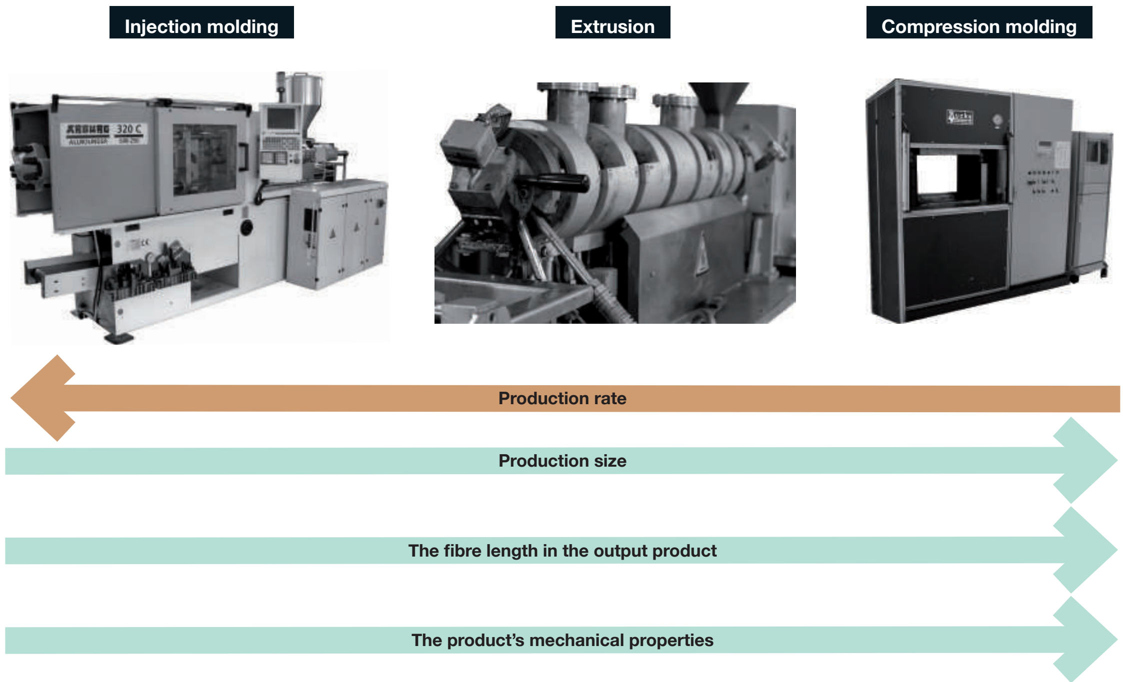

FIG. 2 **Product properties' dependence on the manufacturing technique.**

Extrusion

Extremely short fibers and wood flour are fed freely into the extruder. Alternatively, slivers and yarns can be fed to the thermoplastic stream through an input to the extruder or with the help of a side feeder. The homogeneity of the fiber distribution within the matrix is defined by the fiber loading, the applied temperature and the right selection of the extruder elements.

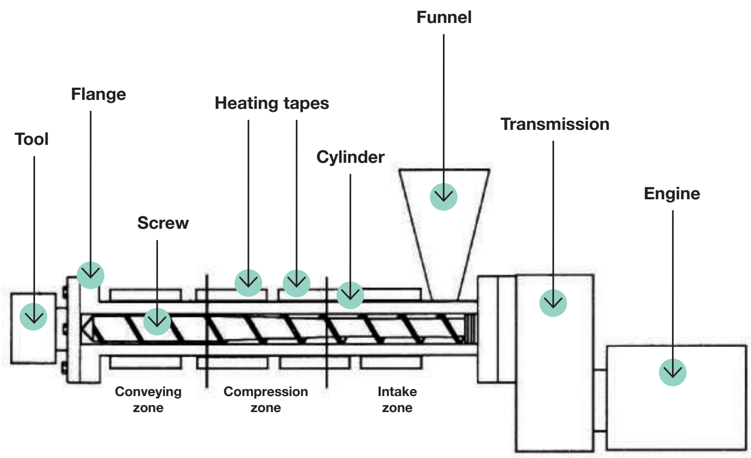

FIG. 3 **Schematic of the extrusion process.**

ADVANTAGES

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

DISADVANTAGES

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

Compression molding

Press forming or compression molding of natural fiber thermoplastic composites is normally used in the automotive industry, especially for interior parts. The preform, containing natural fibers mixed with the thermoplastic matrix (see Chapter 3), is preheated to a temperature that ensures low viscous flow of the polymer inside the natural fiber bundles, and then pressed into the required shape.

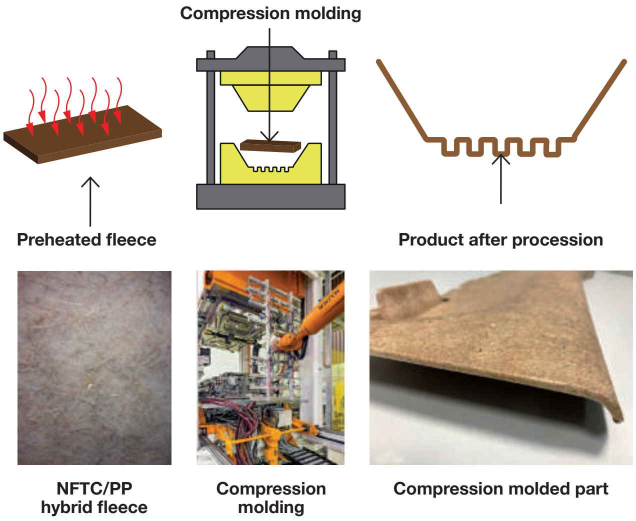

FIG. 4 **Assembly made from natural fibers with thermoplastic matrix (PP).**

Direct injection molding

A modified technique has been developed for direct injection molding with natural-fiber sliver and thermoplastic granulates. This method is also widely referred to as direct long fiber reinforced thermoplastics (D-LFT). The process involves blending the fibers, 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 5. KraussMaffei Company has developed another method for direct injection molding, in which an extruder mixes natural-fiber bundles and the thermoplastic polymer together. Then the extruded material is introduced as a melt directly into the injection mold.

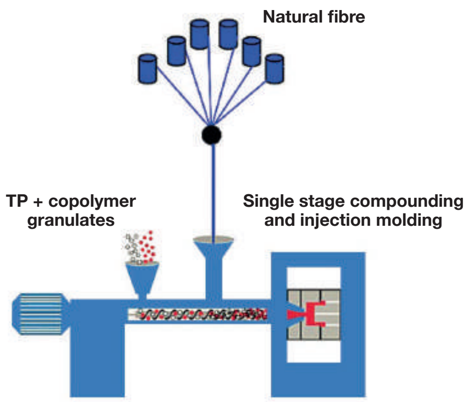

FIG. 5 **Direct injection molding of natural fiber and thermoplastic granulates.**

Thermosetting composites

Thermosetting natural fiber composites represent almost one third of the natural fiber composite applications (Nova Institute, 2007). In principle, all the manufacturing processes known from high-performance fiber composites, as shown in Figure 6, can be applied for natural fibers as well. The most important processes are described succinctly in the following figures. The low viscosity of the thermoset matrix before curing enables the system to impregnate the textile structure easily, resulting in structures with high mechanical an physical properties.

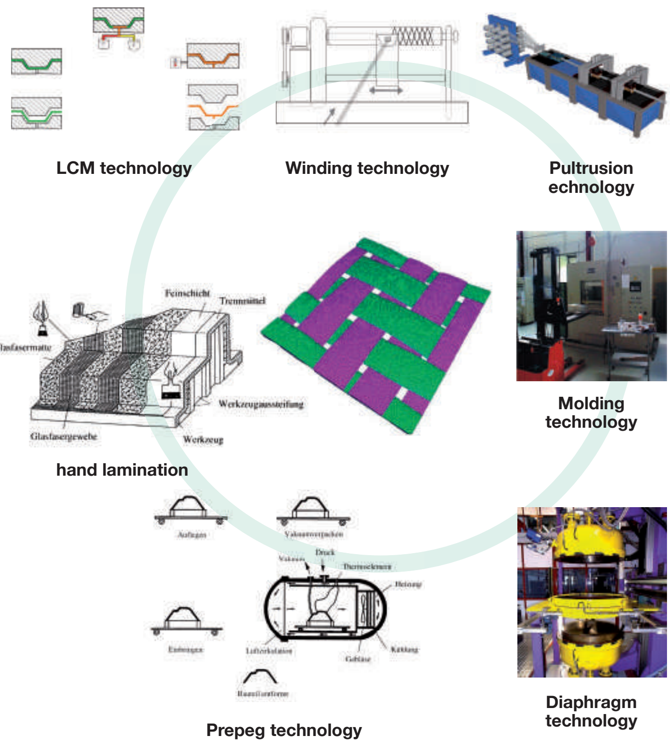

FIG. 6 **Overview of the manufacturing processes.**

Liquid composite molding (LCM) process

There are now a number of variants of the LCM technique, like RTM (resin transfer molding) or VARI (vacuum-assisted resin infusion). The main process for the RTM technique is shown in Figure 7. Resin and hardener are pumped separately to the mixing head before injection into the mold and curing, although sometimes they are premixed and injected as such.

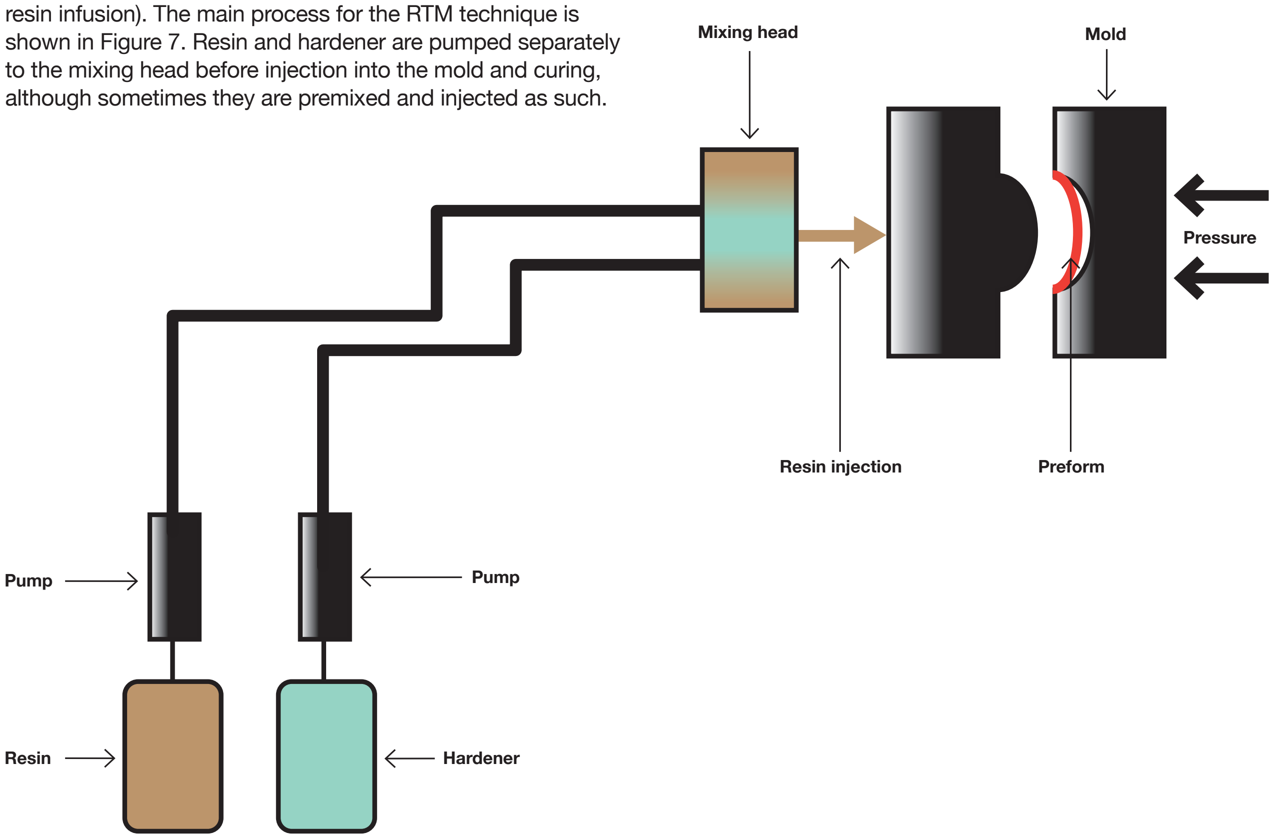

FIG. 7 **A schematic view of the RTM technique.**

In the VARI process, the resin is allowed to infuse into the fabric smoothly and slowly for wet out, assisted by the vacuum. More extensive information on both RTM and VARI is given in the 2012 edition of the book "Flax & Hemps Fibers: a natural solution for the composite industry"

Press forming

The press-forming process for thermosets is the same as the one for thermoplastics, with the exception that the mold will be heated at a constant high temperature to cure the resin system in a very short cycle time. The principle of the process is shown in Figure 5. Bulk molding compound (BMC) is a premixed material (fiber + resin system) that is placed in the mold. When pressure is applied, the material fills the mold. In the sheet molding compound (SMC) process, a semi-finished flat sheet is placed in the mold, and the material will fill the mold by flow processes when pressure is applied.

Out-of-autoclave processing (OOA)

Because the impregnation in prepreg materials has already been completed to a large extent, prepregs allow faster production rates compared to dry preforms. Synthetic fiber prepregs were developed for high-end applications that required autoclaves to precisely control the curing process. The disadvantage of autoclaving is that it usually slows down the production of a part. As a result, out-of-autoclave processes have been developed to consolidate prepregs without the need for an autoclave. One such process is similar to compression molding of thermoplastic composites. The prepregs are placed in a mold in the desired stacking sequence, and the heated mold is closed to shape the part and complete the curing reaction. OOA processing is preferred when there is a need to produce larger series.

Two other techniques, pultrusion and filament winding, are used as well. These are described in the 2012 edition of the book *"Flax & Hemps Fibers: a natural solution for the composite industry".*

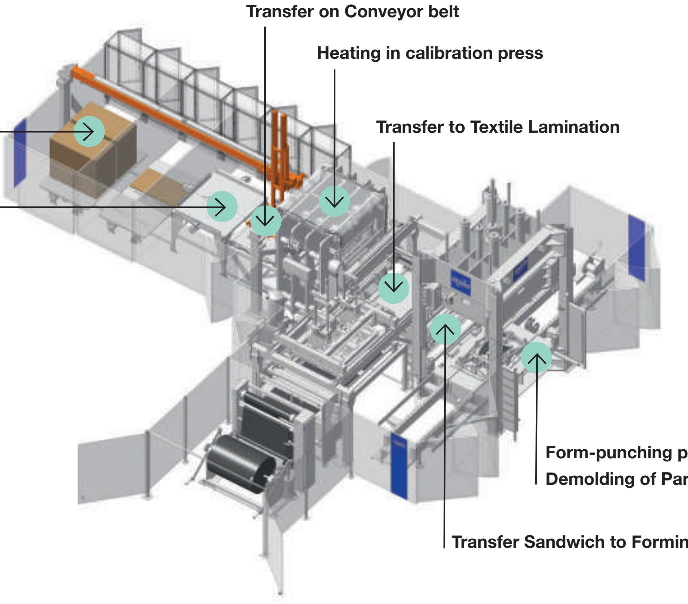

FIG. 8 **Process flow for NFPP.** (Oneshot – FRIMO – source: NMB)

PROCESS EXAMPLE FOR THE FLOW FOR NFPP (HYBRID MOLDING)

In the automotive industry, new processing lines have been installed for the production of natural fiber PP (NFPP) parts, i.e. for interior door paneling. An innovative line is now under construction as shown in Figure 8, to serve a series production for automotive applications.

This highly automated processing line will produce structural elements from flax- and-or hemp-fiber/thermoplastic nonwovens. There are also various developments in combining the press-forming and injection molding processes to reinforce flat structures, using local injection-molded substructures like ribs, local fixation points etc. Such a combination of processes is already in use by the Neue Materialien Bayreuth GmbH. The example in Figure 10 shows a demonstrator part for that combination. Those injection-molded parts could also be reinforced with natural fibers to improve the strength and stiffness of those elements.
Combined with an injection-molding machine, subcomponents could be injected directly in the mold as shown in Figure 10 to produce structures in a very efficient way for series production in the automotive industry.

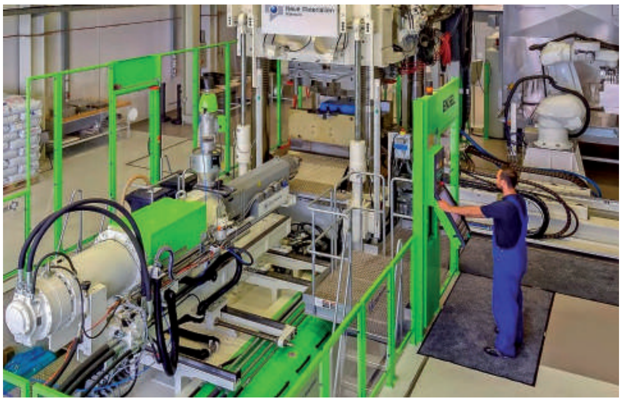

FIG. 9 **Combination of injection and compression molding.** (Neue Materialien Bayreuth)

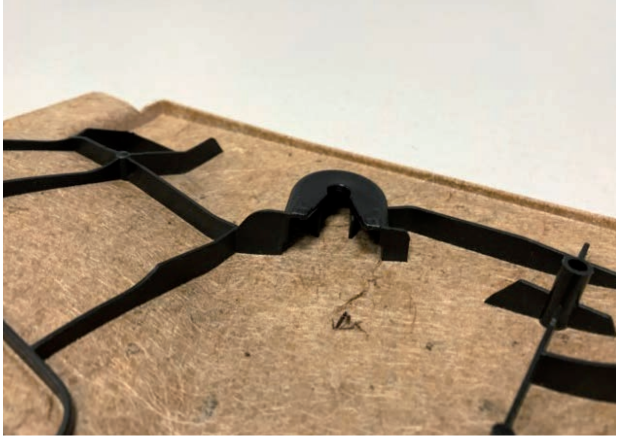

FIG. 10 **Directly injected subcomponents on compression-molded parts.** (Frimo)

2. Production techniques for Flax and Hemp fiber composites and selected application examples

Compression molding

Automotive

The compression molding process – especially used with thermoplastic-matrix systems – is well known in various applications for a number of end uses, and is described in Chapter 7.1. Short cycle times are essential in the automotive industry, so there are a number of different applications.

Since 2015, all vehicles in the European Union must be at least 95% reusable and 85% recyclable in terms of vehicle mass (Directive 2000/53/EC). On top of this stringent material requirement, the CO_2 emissions of these vehicles had to drop to values below 130 g CO_2/km by 2015, with a target of below 95 g/km CO_2 to be achieved by 2020. Similar regulations have been implemented in the United States (US 2025 CAFE, diesel cars < 115 g CO_2/km) and China (Phase 3 in 2020, diesel cars < 135 g CO_2/km).

To meet these requirements, there is a constant demand in the automotive industry for more lightweight materials that are partially or fully recyclable. Flax and hemp fiber composites offer elegant solutions to this, as they are lightweight, CO_2 neutral, non-abrasive, and cost-efficient with high mechanical properties. They also offer other relevant properties for automotive applications, such as vibrational and acoustic damping combined with thermal insulation. The use of composites in vehicles has considerably increased over the years. In 2010, only 14% of a vehicle's total weight could be attributed to plastics and composites, whereas the percentage is projected to rise to 23% by 2020 (JEC Overview of the global composites market, 2017). This makes it the fastest-growing material class in the automotive industry.

Achieving and maintaining high production rates is vital in this industry, so thermoplastic prepreg materials are often used to drastically reduce the time needed for impregnation and consolidation. In this way, compression molding can be used to produce door and instrument panels, headliners, and trunk side trims. Production times are in the range of minutes for these semi-structural parts. Since the loads are limited in these parts, cost-efficient flax or hemp fiber random mats are often preferred as the reinforcing fiber architecture. And because the fibers are non-abrasive, mold service life is much longer than with synthetic fiber parts. Random mat prepregs that can be overmolded have recently entered the market. The principle is simple: a random mat prepreg is consolidated using compression molding and subsequently inserted into a specially designed mold cavity for injection molding, as explained earlier in this chapter.

FIG.11 **The approximately 45kg of natural fibers in a Mercedes S-Class.** (Source: Daimler)

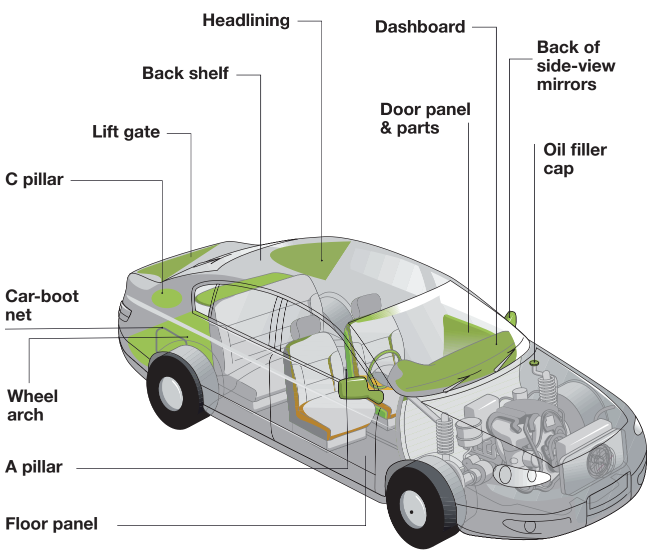

FIG. 12 **Various automotive parts in which flax and hemp fiber composites have already been integrated.** (Source: CELC)

Parts that need to be stiffer for use in somewhat more structural applications cannot be made from random mats alone, as the part thickness and weight would be excessive. Therefore, they are reinforced with oriented prepregs or grid structures. The part can be either fully made from these oriented prepregs, or partially by using the oriented prepregs as skins in combination with a core material to produce a sandwich panel.

ADDED VALUE OF FLAX AND HEMP

- **Lightweight parts reduce CO_2 emissions of the vehicles**
- **Semi-structural parts can be produced**
- **Short processing lead times**
- **Low fiber abrasiveness leads to longer mold service life**
- **Recyclability is less problematic than for synthetic fibers**

FIG. 14 **Console part made from flax fiber/PP random mat reinforced with a grid.** (PowerRibs - BComp)

FIG. 15 **Overmolded car door panel containing flax fiber/PP random mat on the inside and pure PP on the outside to form the intricate details.** (FibriPlast Hybrid by Ecotechnilin used by Mercedes - E class)

FIG. 13 **Compression-molded door panels.** (FibriPlast - Ecotechnilin)

Design

The design branch is often one of the most innovative material sectors. Continuously looking for visually appealing and new materials, they produce both structural and non-structural parts. Other advantages offered by flax and hemp fibers specifically for this sector are: unique touch, low weight, lack of abrasiveness, biodegradability and flexibility to create complex shapes. One such designer, Christien Meindertsma has teamed up with flax fiber suppliers to create a chair made from woven and non-woven flax prepregs. The woven flax fabric consists of flax fibers commingled with PLA filaments.

A flax-fiber random mat pre-impregnated with PLA filaments was used in between the woven material. Meindertsma designed the chair to be made from one composite plate measuring 60 cm by 90 cm, with minimal material waste. Compression molding is used to shape the chair parts. The use of a single polymer, PLA, ensures that all layers adhere perfectly to one other, creating a solid structure that can withstand significant loads. Moreover, both flax fibers and PLA are fully biodegradable under the right conditions, eliminating recycling difficulties. Flax and hemp fibers can also be colored by using (biodegradable) dyes, offering yet another advantage of these materials for the design sector.

ADDED VALUE

- **Structural properties of the fibers**
- **Design freedom, flexibility in shaping**
- **Aesthetics**
- **Biodegradability**

FIG. 16 **Flax chair containing woven fabric produced from non-woven flax fiber/PLA prepregs.** (Groupe Depestele and Enkev) (Christien Meindertsma / Label Breed)

FIG. 17 **A box made from a flax fiber/PLA woven prepreg. The weave contains PLA filaments that can be melted to impregnate the flax fibers. In this application, the filaments were only partially melted to give the box a more natural aspect.** (Varian by CultureIN used in Designerbox 36 by Philippe Nigro)

Another example of the versatility of these fibers is the Designerbox X LINEN project. The designer uses a flax/PLA prepreg in which he can soften and partially melt the PLA filaments. After this, the material is pressed into a mold and cooled to form the final shape. Initially created to offer new shaping opportunities in architectural spaces or in transportation, this fabric rigidifies itself when heated. The material maintains the visual aspect of the flax fiber.

Music & audio

The interaction of flax and hemp fibers with acoustic vibrations enables their use in audio and music applications. Music instruments have been developed with a unique acoustic spectrum such as guitars and ukuleles.
A new-generation speaker diaphragm consisting of a quasi-UD weave between two sheets of glass fibers is now on the market. With its very low density, high stiffness and a straight cone, the sandwich structure delivers tighter bass.

ADDED VALUE

- **Unique acoustic spectrum**
- **Tighter bass sounds**

FIG. 18 **Speaker diaphragm consisting of a quasi-UD flax fiber/PP weave in between two glass fiber sheets.**
(Quasi-UD weave Biorenforts by Terre de Lin used by Focal)

Vacuum infusion and resin transfer molding (RTM)

Automotive

More structural parts in automotive are produced by VARI or RTM. A good example of this is the recent development of a car roof top and hood for sports vehicles. The parts consist of twill 2/2 flax-fiber weaves with a 0°/90° grid at the outer surface, in an epoxy matrix. Both hood and roof top were produced using vacuum assisted resin infusion. Apart from the high stiffness required for these parts, the impact behavior is important as well. In the event of a crash, as much energy as possible should be dissipated by the hood. During a crash the composite frequently splinters, ejecting sharp fragments at high speed, which can be dangerous for the driver and passengers. Flax and hemp fiber composites, however, possess good impact behavior, dissipating more energy than carbon fiber composites (for instance). Aside from increasing the stiffness of the hood, the grid structure also adds to its integrity during crashes by keeping the fragments together. An additional advantage of the grid is that it guides the resin during the infusion process, which lowers the amount of consumables needed. Extrapolating to serial production, the same result can be obtained with prepregs followed by an autoclave curing step.

FIG. 19 **Car roof top and hood made from a twill 2/2 flax fiber weave and a reinforcing grid.** (ampliTex and powerRibs – BComp – Electric GT)

ADDED VALUE

- **Lightweight**
- **Structural integrity**
- **Safe crash behavior due to decreased splintering**
- **Grids guide resin during impregnation, reducing consumables**

Van.eko has incorporated biosourced composite materials into its new electric scooter, the Be.e. The result is a sleek look, frameless (like a Vespa), with a partially biobased resin and flax- and hemp-fiber body, designed by the duo Maarten Heijltjes and Simon Akkaya from the Dutch design agency Waarmakers. The scooter is relatively light (95kg) and can reach 55km/h, with a 60km battery life and a 3-hour charge time.

FIG. 20 **Scooter with a flax- and hemp-fiber random mat reinforced body.** (Flax fibers - Van de Bilt Zaden en Vlas used in Be.e scooter – Van.Eko)

Construction

Components for building can be quite large. This makes closed-mold processes, such as RTM, very expensive and nearly impossible to execute. This is especially true when the part is not designed for production in large series. Vacuum infusion offers a solution to these problems, as it requires a single mold half, which can be produced from less expensive materials.

Here again, flax and hemp fibers offer many advantages. As well as being structurally sound, they can help regulate indoor climate conditions due to their moisture absorption capacity, and they also provide thermal and acoustic insulation.

ADDED VALUE

- Structural performance
- Thermal and acoustic insulation
- Assists in indoor climate regulation
- Large parts can be produced cost-efficiently

FIG. 21 **Large facade panel encapsulating a screen mounted above the entrance of a local movie theater in Paris. The panel is reinforced by a flax fiber weave.** (Woven flax fabric /Groupe Depestele used by Pathé Cinema in Paris, France and produced by Multiplast).

Sports & Leisure

Composites and sport applications are closely intertwined. Surfboards have been made for decades out of E-glass fiber reinforced polyester. More and more producers of these sporting goods are discovering the added value flax and hemp fibers can bring to their products. The frequent use of thermosets is not surprising, since high-quality surfaces and durability in terms of mechanical and abrasive performance are often desired for these applications.
The lower density of flax and hemp fibers could lead to some weight savings in sporting goods compared to glass fiber composites (not in comparison with carbon fiber composites, though), but more important are the impact resistance and vibrational damping. For instance, for surf or stand-up paddle (SUP) boards, the material should be light and capable of with-standing bending or damage when the surfer or paddler falls or hits a rock. Because of their lower density compared to glass or carbon fibers, products can be made thicker for the same weight. This can lead to significantly higher resistance to bending loads and local stresses.

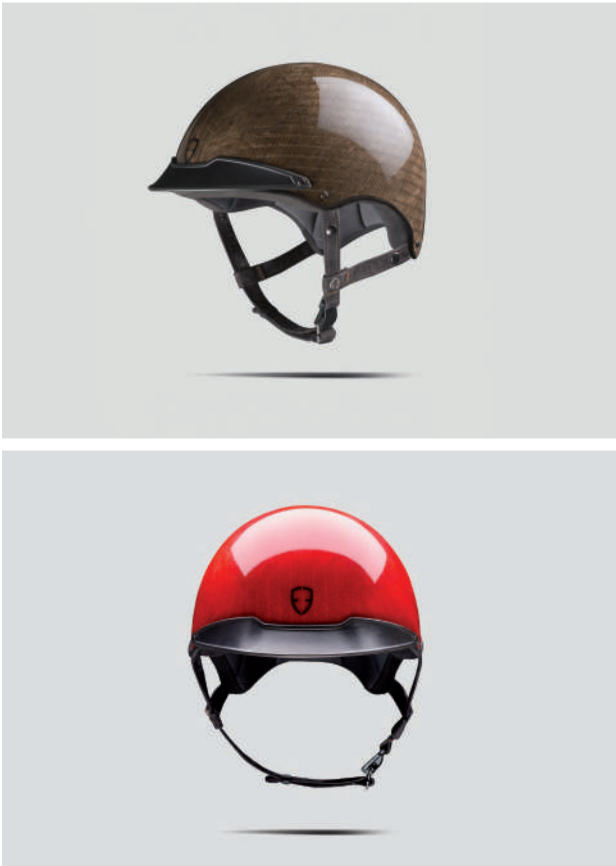

FIG. 22 **Bicycle helmet made with a biaxial flax fiber non-crimp fabric. The flax fibers can be colored to produce an aesthetic look.** (Biaxial fabric Biorenforts - Terre de Lin used by Egide)

FIG. 23 **Stand-up paddle board (SUP) combining a woven flax fiber reinforcement with a grid achitecture to provide additional stiffness and indentation resistance.** (ampliTex and powerRibs by BComp used by Greenboats)

ADDED VALUE

- Unique look
- Enhanced user experience
- Indentation resistance

FIG. 24 **Leisure boat comprising several deck parts made of woven flax fiber epoxy composites.** (ampliTex - BComp used by Greenboats)

Design & Fashion

High surface quality and impeccable impregnation are vital in the production of parts to be integrated into luxury products such as furniture and high-end jewelry. Often, design tolerances are very narrow, as the parts need to be seamlessly integrated in the final design. This is again an advantage of RTM processing, since the dimensional variations of the parts are very low. Gel coats can also be applied on top of composite laminates as a protective layer with a glossy appearance.

FIG. 25 **These watch faces are made from colored UD flax fiber layers impregnated with epoxy resin containing a UV stabilizer.** (Unidirectional flax fibers – Bcomp used by Hublot)

© SaintLuc design by Jean-Marie Massaud

Field chairs © SaintLuc design by Philippe Nigro

ADDED VALUE

- Unique look
- Narrow design tolerances

Codet table and Hamac chairs © SaintLuc design by Jean-Philippe Nuel

Nil chair
© SaintLuc design by
Jean-Michel Wilmotte

Armchair
© SaintLuc design by Jean-Marie Massaud

Tools
© SaintLuc design by Joran Briand

FIG. 26 **Several design chairs with flax fiber non-crimp fabric reinforced shells produced using RTM.** (+/- 45° non-crimp fabric, Biorenforts - Terre de Lin)

Out-of-autoclave processing

Sports & Leisure

Large-series production is typically encountered in the sports industry. In cases where a certain flexural behavior of the parts is desired, such as in skateboards, skis and snowboards, the addition of flax or hemp fibers can offer significant advantages. In general, too-stiff products result in a less desirable user experience due to a lack of deformation and failure to adapt to terrain conditions. Adding flax or hemp fibers to these products helps to adapt the stiffness to the desired (lower) value and increases the capacity to absorb vibrations, therefore providing more comfortable user conditions.

FIG. 27 **(Right) Snowboard containing several layers of unidirectional flax fibers** (FlaxTape by Lineo used by Jones)
(Left) Skis containing flax fabrics. (UD flax/carbon Biorenforts - Terre de Lin used by Salomon)

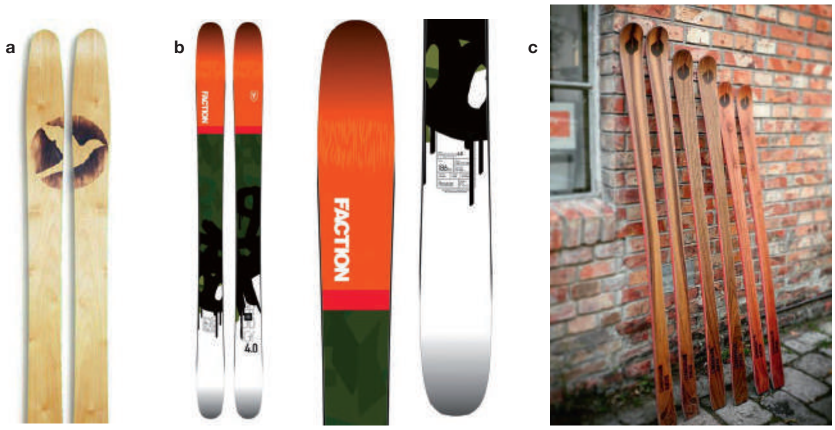

FIG. 28 **Various ski manufacturers integrate flax fibers into their designs to reduce vibrations and to enhance the user experience.** (Reinforcements – BComp used by (a) Early Bird (b) Faction and (c) Ûnique skis)

ADDED VALUE

- **Unique look**
- **Enhanced user experience**
- **Shock absorption and vibration damping**
- **Faster production rates**

Ready-to-use sandwich panels

Sandwich panels are very popular in the composite industry due to their much stiffer behavior than thin laminates, for only a marginal increase in the weight of the part. In principle, sandwich systems are designed with thin, stiff skins, reinforcing fibers and matrix systems based on thermoset or thermoplastic polymers.

Because they have very low density, flax and hemp fibers outperform several synthetic fibers in bending, especially when used in sandwich panels. This explains why a number of producers are marketing ready-to-use sandwich parts.
The skins can be produced from all possible flax or hemp fiber architectures. Both thermoset and thermoplastic composites can be used. Core materials are either balsa wood, honeycomb (paper or plastic) or plastic foams. Flax or hemp random mats can also be used as core material, providing the additional advantage that recycling of the material is made easier when it is combined with flax or hemp fiber composite skins.

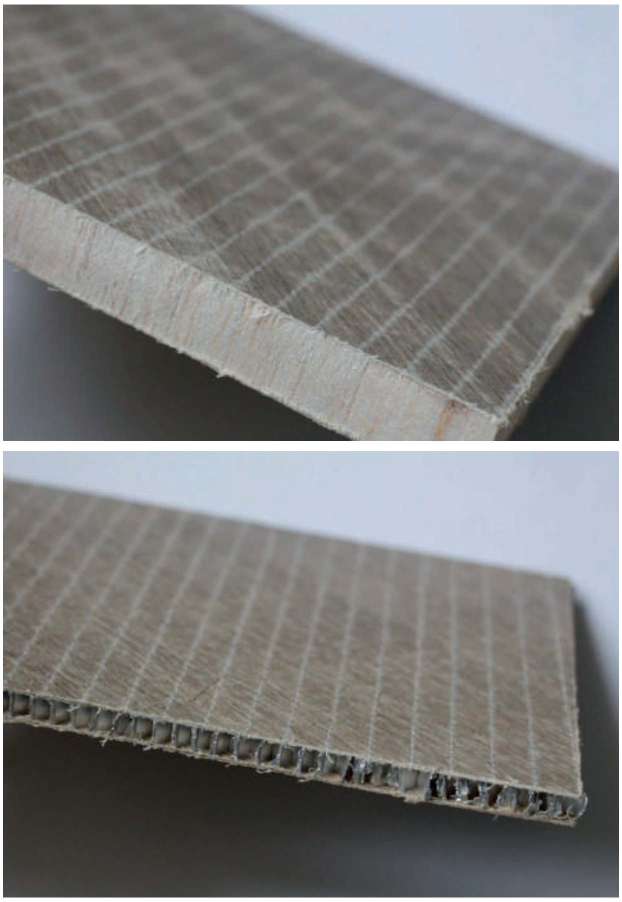

FIG. 29 **(Top) Sandwich structure with flax fiber non-crimp fiber / PLA skins and a core of balsa wood. (Bottom) Identical skin layers as the former, but the core is a paper honeycomb.** (Flaxcomp CP / Dedienne Multiplasturgy)

FIG. 30 **A staircase made from a sandwich composite using a plain 1/1 flax fiber woven composite as skin and a balsa wood core.** (Nattex Panel by Dehondt Composites)

FIG. 31 **Flax fiber random mat/furan fire-retardant sandwich, used as side panels in a lightweight trolley for aircrafts, reducing fuel consumption.** (Fibrirock sandwich, Ecotechnilin, used in SmartCart)

Prospective applications & recent developments

By 2025, synthetic fiber composites will become increasingly challenged by other materials on cost competitiveness and recycling possibilities (Overview of the global composite market, JEC, 2017). Three key industries in which this could play a major role are transportation (in particular automotive), aerospace, and construction, so these are the industries in which natural fiber composites have an enormous potential.

The Sinfoni project in France has successfully produced a flax and hemp fiber reinforced train cabin in cooperation with Bombardier. Produced by both vacuum infusion and hand lay-up, the demonstrator complies partially with the stringent fire regulations (EN 45545-2) imposed by the industry, although the hand lay-up parts still need further improvements. Using these fibers instead of E-glass fibers made it possible to reduce the cabin weight by more than 20%, which would lead to significantly lighter trains. Less weight on the chassis could also minimize maintenance frequency and lower the minimum power requirements for locomotives.

This project showed that although flax and hemp fibers are natural materials, it is possible to meet the stringent requirements of fire safety imposed by different sectors. New projects are currently being prepared to broaden the range of parts produced with natural fibers in the transportation sector.

Penetration of the aerospace industry has been difficult for flax and hemp fibers because of the very stringent safety and performance regulations. However, with the introduction of the European Space Agency's Clean Space Program, these fibers have attracted their attention. Debris has become a pressing issue, and the Clean Space Program seeks to reduce waste in space. Uncontrolled objects flying in orbit pose severe risks to satellites, shuttles and astronauts.

FIG. 32 **Train cabin containing 37.5 wt% of woven and non-woven reinforcements in a polyester resin.** (F.R.D.)

Tommaso Ghidini,
Materials Technology Manager, European Space Agency - ESA, The Netherlands

"Mechanical damping is very important. During takeoff, we have very high vibration levels and have to accelerate a huge rocket with a satellite up to 28,000 km/h in order to escape the gravitational force of the Earth. This imposes very strong vibrations on the launcher and its payload (i.e. the satellite), which is very fragile. So whenever we can, we need to significantly reduce vibration levels. A material that has damping properties comparable to our requirements is welcome.
Flax fiber has a high ecological potential, interesting for our CLEAN SPACE program and also for its strong vibration damping property and the availability of the material."

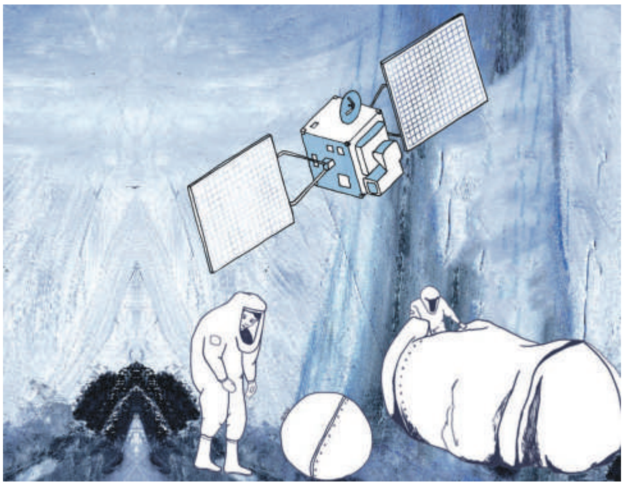

FIG. 33 **The ESA Clean Space Program seeks to reduce debris in space by using hybrid natural fiber composites.** (Source: ESA)

Plant fiber composites could disintegrate faster by returning to earth. In collaboration with ESA, tests are being performed with Bcomp's flax 0°/90° grid structures, commercially known as powerRibs®. Lighter and stiffer parts are produced by adding the ribs to a carbon fiber reinforced laminate, thereby reducing fuel consumption. Vibrational damping by the flax fibers also helps to reduce the mechanical loads acting on the very fragile payloads sent into space.

A recent trend in automotive applications is bringing flax and hemp fibers to the surface of parts, as manufacturers are always looking for innovative surface aspects. As opposed to synthetic fibers, natural fibers can be colored and can produce unique surface effects in molded decorations. Here, the quality of the fiber finish and aesthetic appearance of the fibers is especially important.

FIG. 35 **Decorative designs based on flax & hemp fiber composites are becoming increasingly popular in the automotive industry. In addition, in-mold decorations can produce even more visually appealing parts.** (BComp)

The FlaxPreComp project in Belgium decreased the energy consumption and manual labor involved in the preform production process by integrating scutched fibers into the preforms instead of using hackled fibers. Results show that the composite performance of scutched fibers can be identical to composites made with hackled fibers. In the future, this will not only lead to architectures with increased mechanical properties, but also strengthen the market share of flax and hemp fibers in the composite industry.

FIG. 34 **Demonstrator table from the FlaxPreComp project, where low-twist flax rovings were successfully woven to produce a weave with excellent mechanical properties.** (Flipts & Dobbels)

The Technical University of Eindhoven produced the world's first fully biocomposite footbridge in October 2016. Installed on their campus, the footbridge is part of a research project that investigates the long-term mechanical behavior of the composites. Flax and hemp fiber reinforcements were used in various architectures to reinforce the bridge, combined with a partially biobased epoxy resin. The reinforcements were glued to a PLA foam core. Sensors register the bending that occurs in the bridge over a one-year period.

FIG. 36 **A 14-meter-long bridge made from flax & hemp fiber composites in Eindhoven, The Netherlands. The bridge was built as part of a research project by the Technical University of Eindhoven.** (TU Eindhoven)

Acknowledgements

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VIII
Are Flax and Hemp Fiber Composites Sustainable?

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This chapter focuses on answering the questions: What is sustainability? How can it be measured and improved in relation to natural fiber-reinforced composites? Based on the concept of product-based integrated environmental protection, the chapter will discuss input/output of a product life-cycle, explain what the stages and boundaries of a Life Cycle Assessment (LCA) are, and bring the reader up to date on the potential environmental impacts of a product throughout its life cycle. This information is intended to enable the reader to evaluate the significance and the limitations of an LCA. Finally, the chapter will give an overview of existing LCAs for flax and hemp fiber processing and flax fiber-reinforced composites and compare these with other materials.

Sustainability

Biobased products often have a sustainable image. While this can be justified, it is not always the case. Therefore, it is necessary to clarify the definition of sustainability.

The concept of sustainability has its basis in the late-medieval German forestry. The term "sustainability" can be traced back to Hannß Carl von Carlowitz, a Saxonian chief mining officer. In 1713, he introduced the concept of "sustainable" (German: nachhaltig) silviculture in his book "Sylvicultura oeconomica", where he advocated prudent management of the forests (Grober, 1999). In those days the sustainability concept was used by forestry bodies for economic reasons:

- **Static sustainability: Protection of the forest areas and the timber stock.**
- **Dynamic sustainability: A forest management which guarantees a consistent quantity as well as quality of timber yield. (Nutzinger & Radke, 1995; Speidel, 1984; Diefenbacher, 2001)**

In the 19th century, the concept of sustainable forestry was so successful that it inspired emerging forest science in other countries e.g. the United Kingdom and the United States of America. The concept was also applied to other sectors such as in the field of fisheries (Diefenbacher, 2001). Today, a comprehensive meaning of the term sustainability in respect to forest management includes, beside the economic aspects, the positive characteristics of the forest like the conservation of landscape, ecological protection effects as well as the recreational value of forestry land (Nutzinger & Radke, 1995; Diefenbacher, 2001).

Probably the most important definition of sustainability used in politics comes from the United Nations World Commission on Environment and Development (WCED, 1987) report "Our Common Future", also known as the Brundtland Report. The report was named after Norwegian Prime Minister Gro Harlem Brundtland, for his role as Chair of the WCED (Diefenbacher, 2001). In the report, sustainability is defined as follows:

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (WCED, 1987)

For an understanding of sustainability, it is important to balance economic criteria as well as social and environmental requirements (see Figure 1).

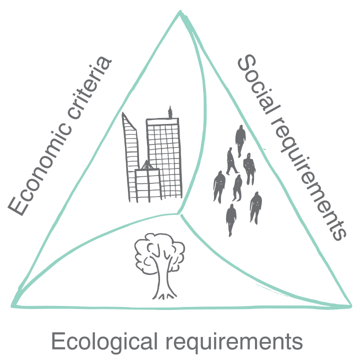


FIG. 1 **The triangle of sustainability, to illustrate the importance of keeping a balance between economic, social and environmental sustainability factors.**

A general concept to assist the implementation of product-based integrated environmental protection is schematically shown in Figure 2. Resources are needed from the very first step in a product life-cycle, displayed as the Factors of Production stage, including the three basic resources land, labor and capital. Emissions (burden) and goods are transported to the next stage of the product life-cycle. At end of life, the emissions and the product itself should preferably be recycled, or, if recycling is not possible, disposed of.

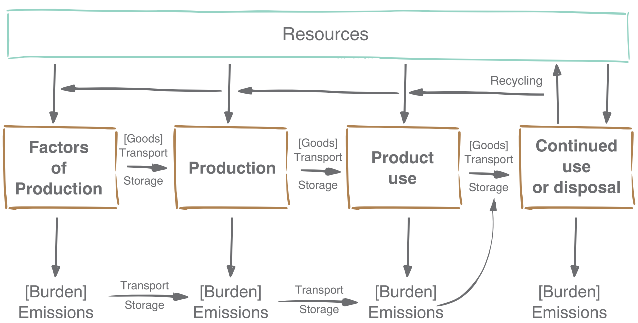


FIG. 2 **Input and output of the product life-cycle** (adapted from Bennauer, 1994).

One means to analyze the environmental sustainability of a product life-cycle (Figure 2) is a Life Cycle Assessment (LCA), an international standardized methodology (DIN EN ISO 14040, 2009) that can be used to evaluate the inputs, outputs and potential environmental impacts over the product life-cycle (InnProBio, 2017a).

The stages of an LCA are shown in Figure 3. The environmental impact categories of a product are, among others, global warming potential (GWP), acidification potential (AP), photo-oxidant formation potential (POP, e.g. summer smog), human toxicity, ecotoxicity, eutrophication potential (EP), ozone layer depletion and radioactive impacts. The most common impact category is the global warming potential in kg CO_2 equivalents, which considers the potential contributions of different air emissions to global climate change. This means that other greenhouse gases, like methane, are converted into kg CO_2 equivalents using a specific characterization factor.

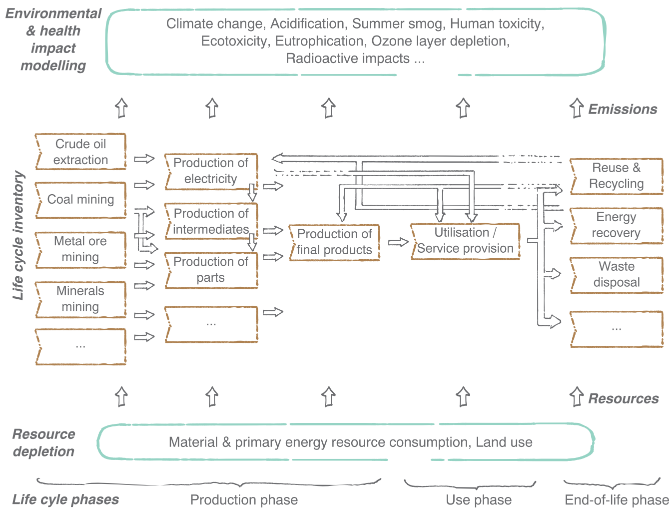


FIG. 3 **Stages of a Life Cycle Assessment** (adapted from JRC, 2016).

According to the standard (DIN EN ISO 14040, 2009) an LCA addresses the environmental aspects and potential environmental impacts, for example, the use of resources as input of the product life-cycle and the environmental consequences of releases as output, such as emissions (burden, compare Figure 2). In the case of the so-called **cradle-to-grave** approach, the product's complete life cycle will be analyzed from raw material acquisition, production, use, end-of-life treatment, recycling and/or final disposal (DIN EN ISO 14040, 2009). In contrast, a **cradle-to-gate** approach is used if an intermediate product is analyzed or if the final function of a product is not yet known. As shown in Figure 4, four phases are part of an LCA study: (i) the goal and scope definition phase, (ii) the inventory analysis phase, (iii) the impact assessment phase, and (iv) the interpretation phase.

An LCA addresses the potential environmental impacts and can be used to identify opportunities to improve the environmental performance of a product. It is worth mentioning that according to DIN EN ISO 14040 (2009), an “LCA does not predict absolute or precise environmental impacts, due to (i) the relative expression of potential environmental impacts to a reference unit, (ii) the integration of environmental data over space and time, (iii) the inherent uncertainty in modeling of environmental impacts, and (iv) the fact that some possible environmental impacts are clearly future impacts” (DIN EN ISO 14040, 2009).

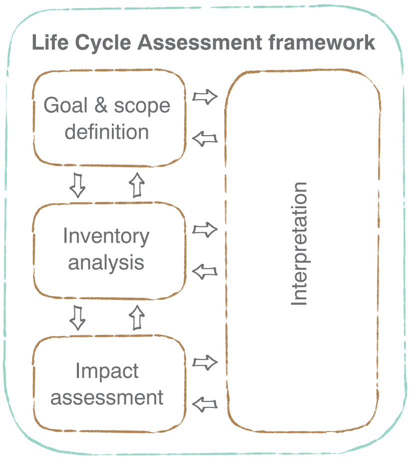


FIG. 4 **Stages of an LCA according to DIN EN ISO 14040** (2009).

Flax

Flax (*Linum usitatissimum* L., Figure 5) is one of the oldest cultivated plants (Waskow, 1995). The species name *usitatissimum*, meaning “most useful”, refers to the fact that flax supplies high-quality fibers, as well as seeds and linseed oil for industrial, nutrient and nutraceutical purposes (Akin, 2010). The production of linen goes back at least to ancient times (Barth & Carus, 2015). The use of flax as a medical herb was mentioned by Fuchs in 1543. Many varieties of *Linum usitatissimum* were cultivated (Dillman, 1953). There are two main varieties of flax, those with long stems and small seeds used for fiber production (namely fiber flax) and those varieties with short stems and large seeds for linseed oil production (namely seed flax). Further intermediate varieties with elongated stems and small seeds, but often basal-branched (namely combination flax) are also cultivated (Schönfeld, 1955; Müssig & Haag, 2015). For an LCA it is important to define whether the plants are cultivated for one product or for several products. Allocation occurs within an LCA whenever more than one product is produced; the environmental impacts need to be distributed over all products (DIN EN ISO 14040, 2009). A schematic overview of the traditional flax fiber process steps can be found in Müssig & Hughes (2012) and Müssig & Haag (2015).

FIG. 5 **Drawing of a flax plant** (Fuchs, 1543).

To perform an LCA for flax fibers or flax fiber composites it is important to first define the goal and scope (Figure 4). Most studies refer the environmental impacts to a mass unit (tonne or kg) of bast fibers (Gonzáles-García et al., 2010, Le Duigou et al., 2011, Barth and Carus, 2015). Due to the fact that flax plants produce different products, like long flax (hackling flax), short flax (scutching or hackling tow) (see Müssig & Haag, 2015), seeds and shives, allocation is necessary for an LCA. Plant-based LCA uses preferably economic or physical (mass, energy, etc.) allocations. The ADEME recommends an economic allocation, if product and co-product(s) have different purposes and a physical allocation (mass, energy, etc.) or if product and co-product(s) have a similar and constant purpose (SINFONI, 2016). Table 1 shows the large effects if mass or economic allocation is used on flax and hemp co-products. In performing competitive LCAs, for example to compare different bast fibers, it can be a challenge to choose the correct allocation methods, as shown in the research studies presented below.

TABLE 1 **Effect on flax and hemp products by using mass-or economic-based allocation over the different co-products** (SINFONI, 2016).

FLAX	MASS-BASED ALLOCATION	ECONOMIC-BASED ALLOCATION
Seeds	**3 %**	**3 %**
Straw	**97 %**	**97 %**
Long flax*	**24 %**	**79,5 %**
Short flax**	**12 %**	**12 %**
Shives	**46 %**	**5,5 %**
Dust	**15 %**	**0 %**

* Scutched fibre bundles for wet spun yarms
** Hackling & schutching tow technical textiles like needle felts

HEMP	MASS-BASED ALLOCATION	ECONOMIC-BASED ALLOCATION
Seeds	**11 %**	**21 %**
Straw	**89 %**	**79 %**
Short hemp#	**24 %**	**50 %**
Shives	**44 %**	**27 %**
Dust	**21 %**	**2 %**

Fibres bundles from the disordered line for technical textiles like needle felts

In a recent study, Barth and Carus (2015) compared flax (Europe), hemp (Europe), jute (India) and kenaf (Bangladesh/India) fibers regarding their sustainability, because these fibers are the most important ones for compression-molded parts in the automotive industry. To avoid distorting effects of allocation and to get comparable LCA data, Barth & Carus (2015) used the same fiber separation process (total fiber line – disordered line) for hemp and flax. The disordered line is different from traditional long flax production by hackling and scutching (longitudinal line; compare Müssig & Haag, 2015) and from traditional hemp production (compare Amaducci & Gusovius, 2010). For hemp and flax, the environmental impact was mass-based allocated to the production of fibers, dust and shives. This scenario was chosen to perform a fair comparison between flax and hemp, knowing that the disordered line is only rarely used for flax (e.g. the TEMAFA line that was used in Sweden in the past and which is currently used in France)[1]. In Figure 6 and 7, the different stages of cultivation, harvest, and fiber processing, which were used in the scenario of Barth and Carus (2015), are shown for flax and hemp, respectively. The results of the LCA are shown in Figure 8. In the LCAs of all four fiber types, fertilizer production had the highest impact of all the stages in relation to the GWP. As shown in Figure 8, flax fiber production releases higher amounts of GHG emissions during field production and the production of pesticides in comparison with the three other fiber types (Barth & Carus, 2015). It should be mentioned here that flax can also be grown organically, which would reduce the GWP.

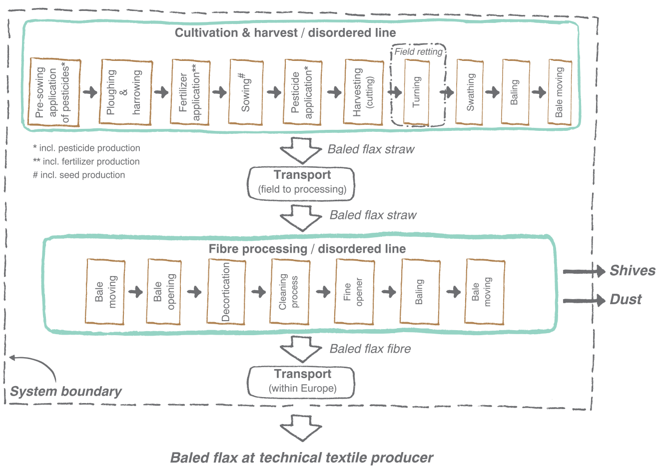


FIG. 6 **System boundary and process chain of flax fiber production (total fiber line / disordered line)** (adapted and modified from Barth & Carus, 2015)[2].

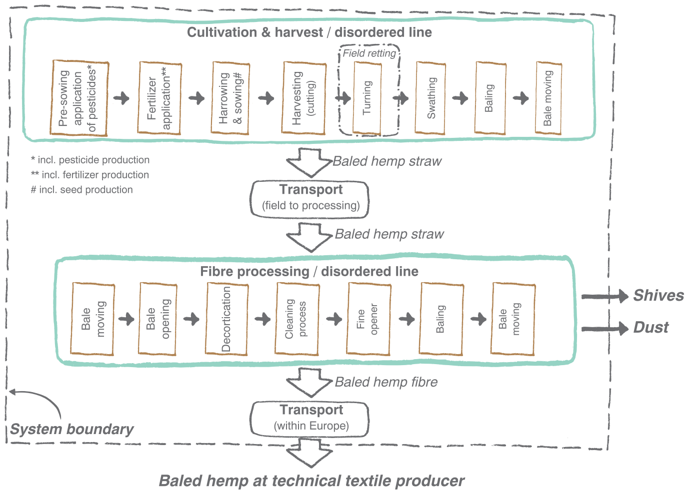


FIG. 7 **System boundary and process chain of hemp fiber production (total fiber line / disordered line)** (adapted and modified from Barth & Carus, 2015).

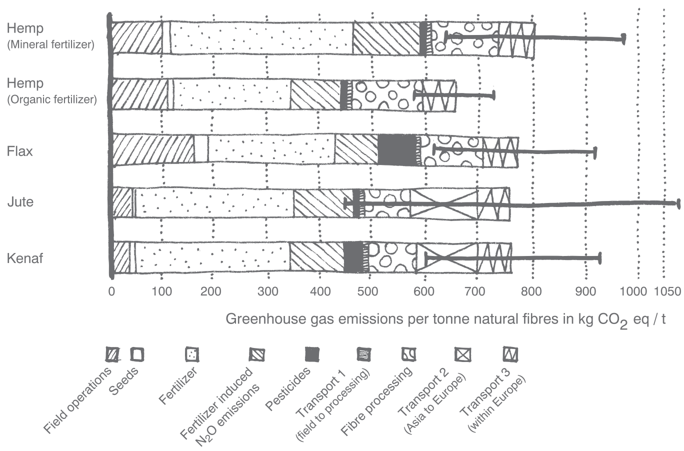


FIG. 8 **Comparison of the (cradle-to-gate) GWP per tonne natural fiber (flax, hemp, jute, and flax, which is processable to needle felts and afterwards to compression-molded composites for interior automotive applications) regarding field operations, seed production, fertilizer production, release of fertilizer-induced N_2O-emissions, pesticide production, transportation from field to processing facility, transportation from Asia to Europe, and transportation to technical textile producer in Europe** (adapted from Barth & Carus, 2015).

GWP is one of the most important potential environmental impacts to consider during an LCA, but the other impacts should not be neglected. In a study by Gonzáles-García et al. (2010) the production of flax and hemp fibers was compared regarding different impact categories. Although Gonzáles-García et al. (2010) performed their LCA for paper fibers and

[1] *The disordered line can be used to produce short flax and hemp fiber bundles. Short flax and hemp fiber bundles are used for compression-molded composites in the automotive industry. For flax, due to the higher market prices for the long flax, it is economically more valuable to produce long flax by scutching, and use the tow for technical textiles like needle felts for the composite market.*

[2] *Comment: Due to the disordered line scenario, the flax stems are cut during harvest in the Barth and Carus (2015) study, to avoid contamination of the resulting fibers with parts of the root. In the traditional longitudinal line, the flax stems are pulled out of the soil, resulting in a complete stem with root and seeds.*

not for composite application, we still use it here to show the influences of different flax and hemp cultivation methods. In contrast to Barth and Carus, Gonzáles-García et al. modeled a specific scenario of Spanish hemp and flax fiber production specifically for the paper industry, including linseed production. Gonzáles-García et al. (2010) performed a price-based allocation for hemp over the production of fibers, dust and shives; and a mass-based allocation for flax over the production of fibers and seeds. Figure 9 shows the relative contributions of field operations, fertilizer use, fertilizer production and transport to the global warming potential (GWP), the acidification potential (AP), the photo-oxidant formation potential (POP) and the non-renewable energy use (EU) for hemp fiber and flax fiber production. Also shown in the study by Barth and Carus (2015) is that the impact of field operations on the GWP is much higher for flax production compared to hemp. In flax production, the field operations also have the highest contributions in other impact categories including AP, POP and EU (Figure 9).

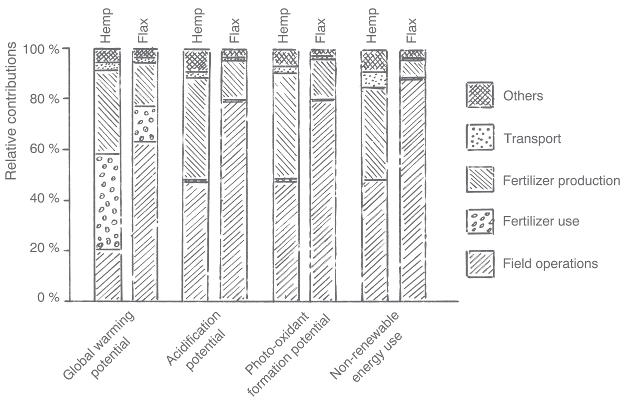
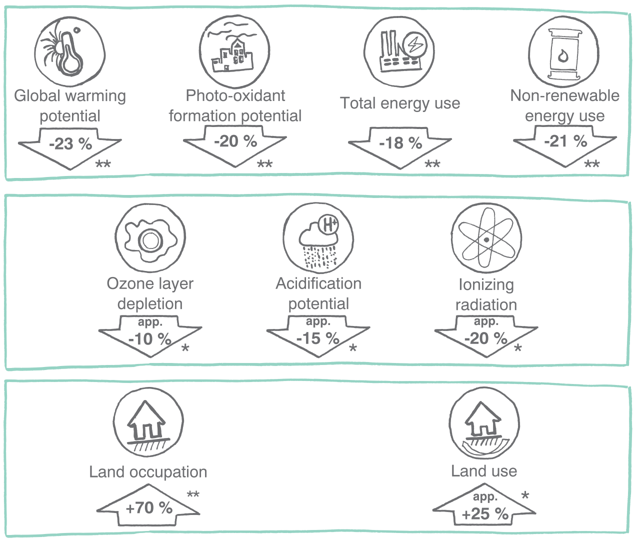


Figure 9: Relative contributions to GWP, AP, POP and EU for fiber hemp and fiber flax scenarios. "Field operations" refers to agricultural practices, including fiber extraction and baling. "Transport" refers to transportation of fertilizers, pesticides (if the case) and fiber bales to further processer. "Others" refers to the remaining processes (adapted from Gonzáles-García et al., 2010).

After this look at the LCA of the processing of natural fibers, we now focus on the use of natural fibers in polymeric composites. In a study of Gueudet et al. (2016a), an LCA was applied to compare a biobased door panel made of polypropylene reinforced with 25% flax fibers and 25% hemp fibers with a 100% ABS-based door panel. The environmental impacts of the biobased panel are lower compared to the petrochemical-based panel in the following categories: GWP, POP, energy use, ozone layer depletion, AP and ionizing radiation (Figure 10). In contrast, the biobased panel has higher environmental impacts compared to the petrochemical-based panel in the categories of land occupation and and use (Figure 10).



** High confidence index
* Average confidence index

FIG. 10 **LCA comparison of a biobased panel made of hemp and flax fiber-reinforced PP to a petrochemical-based (ABS) panel** (adapted from Gueudet et al., 2016a).

In the impact category values of this study, four life-cycle stages are considered: the production of the panel, the assembly, the use phase and the end of life (see Figure 2 and 3). In Figure 11, the impacts of the four stages are shown proportionally for the biobased and the petrochemical-based panels. For both panels, the use phase has the highest impact on the GWP, whereas panel production has the highest impact on POP and ionizing radiation. During the use phase, the biobased panel has a lower impact than the petrochemical-based panel, because the natural fibers enable a lighter composite material than pure ABS. This example shows that it is important to include the (mechanical) properties of the materials as well in a product-based LCA. Considering the use of different bast fibers as reinforcement in a polymer, an LCA should include not just the environmental impact per mass of fibers, but also, for example, the stiffness or the tensile strength of the fibers. In the study of Gueudet et al. (2016b) a cradle-to-grave LCA was performed to take the panel's end-of-life stages into consideration. This contrasts with the LCA of the fibers themselves, where mostly a cradle-to-gate analysis is done, given that many different applications are possible and not all EOL scenarios can be analyzed. When considering the LCA of a specific product, the end-of-life stage should be well thought through. In the study by Gueudet (2016a), it was estimated that the biobased panels will not be recycled at end of life; instead, 33% will be incinerated and 67% will end in waste disposal sites. After the use phase, 11% of the petrochemical-based panel will presumably be recycled; 29%, incinerated; and 60%, end in waste disposal sites. For the end-of-life stage, it is also important to consider the transport of the product to the recycling facility, the incineration plant or the disposal site (see Figure 2).

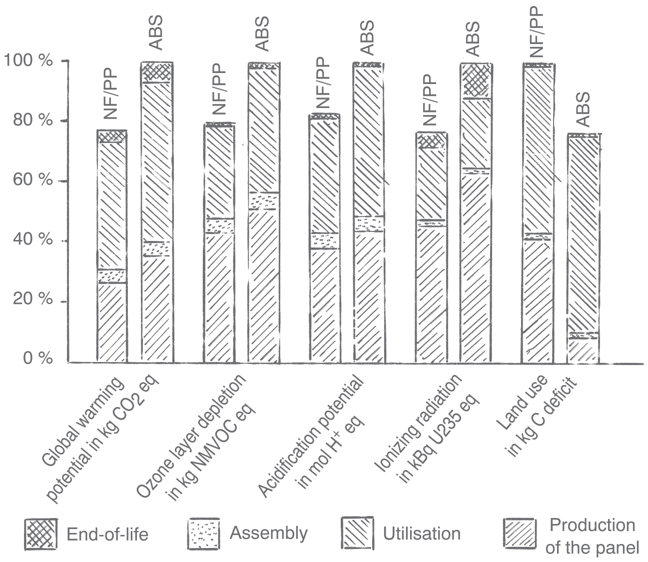


FIG. 11 **Comparison of different environmental impact categories of a biobased door panel (PP reinforced with hemp and flax fibers) to a petrochemical-based (ABS) door panel; on the basis of the life cycle stages: production of the panel, assembly, utilization and end of life** (adapted from Gueudet, 2016b).

In a further study, three different end-of-life scenarios for flax fiber-reinforced thermoplastics were analyzed: chemical recycling, mechanical recycling and incineration (Bensadoun et al., 2016). UD fiber tapes and needle felts were used in a MAPP (maleic anhydride grafted PP) matrix. The chemical recycling technique, where the polymeric matrix is removed and replaced with fresh MAPP, makes it possible to achieve the same mechanical properties as the original composite. However, the chemicals and equipment used show a huge impact to the environment when compared to the two other techniques (Figure 12).

Mechanical recycling led to a reduction of the mechanical properties of 6% to 46% compared to the needle-felt-based composite, and 75% compared to the UD composite; however, the method does perform well enough to be used in non-structural applications. Incineration is a good alternative, because the composite can be fully combusted and “embodies a relatively high calorific value” (Bensadoun et al., 2016). Incineration is not a recycling method, however; a recuperation of the material is not possible. The mechanical recycling technique has the highest environmental gain when compared to chemical recycling and incineration, and it helps to reach the target of the end-of-life vehicle directive.

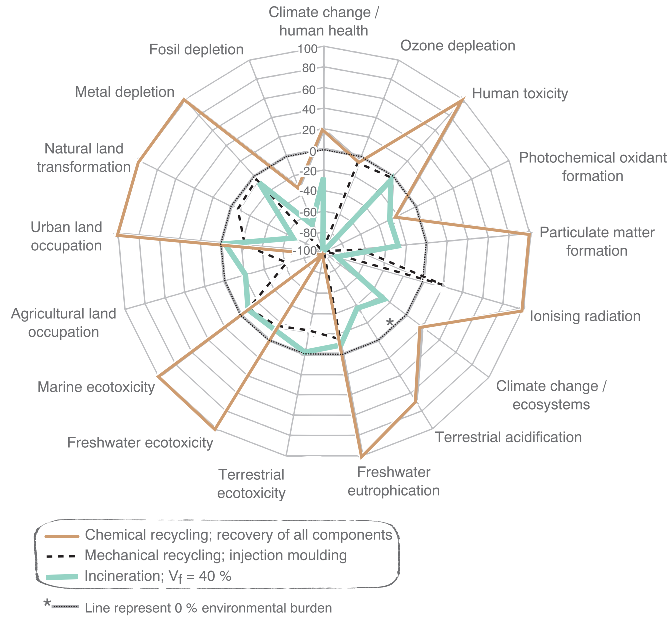


FIG. 12 **Characterization values of three different end-of-life scenarios. The dark grey line represents 0% environmental burden** (adapted from Bensadoun et al., 2016).

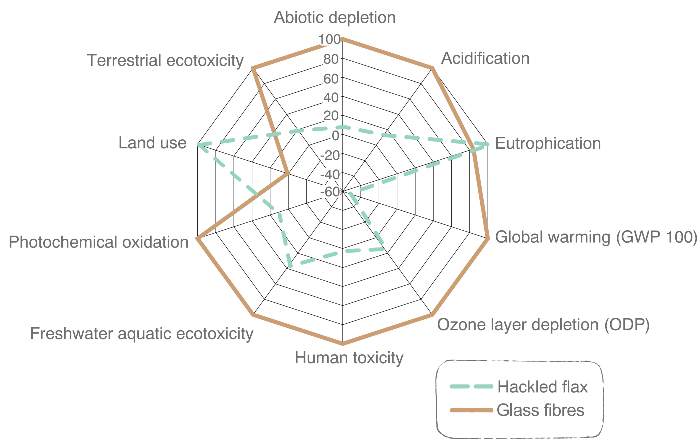


FIG. 13 **Environmental impacts during the production of hackled flax compared to those for glass fibers** (adapted from Le Duigou et al., 2011).

For certain applications and specific load cases, flax fiber reinforced polymers have the potential to replace glass fiber reinforced composites. Hackled flax fibers (Hermès) have a similar tensile modulus when compared to glass fibers, but a lower tensile strength (Charlet et al., 2007; Bourmaud & Baley, 2010). Le Duigou et al. (2011) performed a comparative LCA for hackled flax and glass fibers. A functional unit of one kg of fibers was chosen to simplify the comparison, in the knowledge that mechanical properties being compared are not identical.

As shown in Figure 13, the environmental impact is notably lower for flax fiber production compared to glass fiber production in the categories of global warming potential, ozone layer depletion, human toxicity, freshwater aquatic ecotoxicity, photochemical oxidation, terrestrial ecotoxicity, abiotic depletion and acidification potential. Glass fiber production, however, has lower impacts in the categories of land use and eutrophication potential when compared to flax (Le Duigou et al., 2011). In the aforementioned study, flax production shows a negative GWP, because CO_2 sequestration by photosynthesis was taken into account. It is important to mention that in this study, a cradle-to-product approach was performed so the end-of-life stage is not considered. The allocation in this study was mass-based, including scutched and hackled flax, shives, dust and seeds.
In the same study, the impact of conventional cultivation was theoretically compared to cultivation without treatment. In the theoretical "cultivation without treatment" scenario, the use of fertilizers, herbicides and pesticides was left out. In Figure 14, the reduction of the environmental impact is shown if no fertilizers, herbicides or pesticides were used during the flax production. Their use increases most of the impacts by 50% (Le Duigou et al., 2011). The "cultivation without treatment" scenario does not refer to a realistic scenario for current flax cultivation.

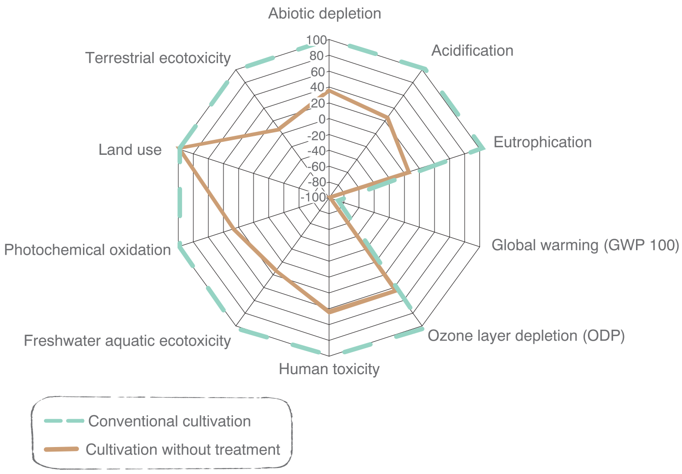


FIG. 14 **Influence of flax cultivation mode (using fertilizers, herbicides and pesticides in the conventional cultivation) on environmental impacts** (adapted from Le Duigou et al., 2011).

Conclusion

As it is understood at present, sustainability includes economic, ecological and social components. This economic-ecological principle originated from forestry and has evolved into global policy guidelines for the responsible management of nature. One method to analyze the environmental sustainability of a product life-cycle is an LCA. This can be used to evaluate the inputs, outputs and potential environmental impacts of the product on the environment over the product life-cycle.

To interpret the environmental impact data, to compare results between different LCA studies, or even compare one's own data with results from other studies, it is important to know the exact background of an LCA. It is essential to know the functional unit and to precisely define the goal of the LCA. For a comparison between different fiber-reinforced polymers, it is important not only to analyze the impact per kg, but also to take the mechanical properties of the fiber and of the resulting composite into account.

Based on the overview in this chapter, it is shown that uniform recommendations for the LCAs of natural fibers are important. Recommendations for the LCA of biobased polymers were developed in recent years under the BiNa project (BiNa, 2018) and will be published in Spring 2018. Recommendations for the LCAs of natural fiber processing shall be performed under the "Integration of environmental indicators of biobased materials in the planning and design processes of industrial products – Methodology and Tools" project (Biomat-LCA, 2017).

The advantages of using natural fibers as reinforcement in polymer components are that a renewable resource is used, lighter constructions are enabled, and the amount of petrochemical-based polymers can be reduced. The environmental impacts are for most of the impact categories lower when compared to pure petrochemical-based products or glass fiber reinforced composites. One constraining factor is that the cultivation of natural fibers requires land use, the production and use of fertilizers and, in most cases, also the production and use of pesticides. It should be obvious that end-of-life options like recycling have to be taken into account as an important topic of scientific research.

One way to reduce the environmental burden of a product is by choosing more sustainable materials. Another is to produce lightweight constructions to reduce fuel consumption, for example in the automotive industry. Natural fiber-reinforced polymers combine renewable resources and lightweight construction potential. The most important impact would be if humans were able to reduce their consumption, and fewer products were produced.

Important steps toward sustainable development in the field of materials are:

- a careful use of resources,
- a closed-loop economy, and
- use of sustainable materials like composites reinforced with flax or hemp fiber, for a minimized impact on the environment.

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The European Confederation of Flax and Hemp – CELC is the only European agro-industrial organization federating all the stages of production and transformation of flax and hemp. Founded in 1951, It is the privileged spokesperson for 10,000 European enterprises across 14 countries, overseeing fiber development from plant to finished product.

CELC encourages dialogue with national and European public authorities. As a think tank and place of market analysis, dialogue and strategic orientation, CELC presides over an industry of excellence in a globalized context.

This mission is guaranteed by EUROPEAN FLAX®, the traceability label for all applications of premium-quality flax fiber grown in Western Europe with each stage of its transformation and processing audited by the leading independent certification body [Bureau VERITAS].

CELC creates an environment conducive to industrial enterprise competitiveness following a three-pronged approach comprising information, defense and promotion. This internationally-focused multichannel strategy stimulates innovation and builds on the performance of natural fibers with proven environmental qualities. A corpus of actions facilitated, produced and promoted by its dedicated platform CELC DEVELOPPEMENT.

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

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