HOW TO COPE WITH MOISTURE SENSITIVITY IN FLAX & HEMP FIBER COMPOSITES

BEST PRACTICE & GUIDELINES

BY THE EUROPEAN SCIENTIFIC COUNCIL OF CELC

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CELC
EUROPEAN CONFEDERATION OF FLAX AND HEMP

MOISTURE SENSITIVITY

INTRODUCTION

Although, flax and hemp fibre composites are susceptible to moisture due to the hygroscopic nature of the fibres, the moisture sensitivity does not prevent their use in demanding applications. On the contrary, **flax and hemp fibre composites are successfully used for load bearing applications in indoor and outdoor conditions as well as in direct contact with water.** Examples include the flax fibre composite bicycle bridge in Ritsumasyl, the Netherlands, figure 1, and the “Gwalaz” flax reinforced trimaran, figure 2. More success stories can be found using the next page.

The performance of **all** composite materials, even those reinforced with glass or carbon fibres, is affected by humid environments, and such effects have to be considered when designing and engineering with composites. As for **all composite materials, precautionary measures are recommended and often necessary** when using flax and hemp fibre composites in humid environments or when they are **immersed,** meaning that they are in continuous contact with liquid water. Composite stiffness, which is generally the most important design property of composite materials, can be lowered by moisture sorption. Prolonged exposure to moist environments can eventually lead to the development of microscopic damage. Other composite properties such as creep resistance might also be negatively affected.

On a positive note, multiple studies have shown that absorption does not necessarily degrade the strength of flax and hemp fibre composites. Moreover, the composite strain to failure increases which benefits the material toughness. The damping properties and fatigue performance at a high number of cycles increase with increasing moisture content.

OUTLINE

In the first section, **best practice guidelines** to cope with the **moisture sensitivity of flax fibre reinforced thermoset composites** are formulated based on the state of the art. Differentiation is made between **general** guidelines, and guidelines for the **indoor** and the **outdoor** climate.

The best practice guidelines, formulated in section 1, are based on a literature review which is discussed in section 2. The influence of the **absorption of moisture** as such, and of a **prolonged exposure** to humidity are evaluated separately.

Future work will include the discussion of a third realistic condition namely flax and hemp fibre composites **immersed** in, or in continuous contact with liquid water. Special caution is strongly recommended in this condition since the effects could be different and more severe than exposure to the environmental humidity and short-term contact with water.

Note that hemp fibre reinforcements and thermoplastic matrices are, for the time being, excluded in the best practice guidelines.

The hemp fibre value chain for composite applications has not yet reached the same level of maturity, compared to flax, and the available reinforcements are mainly limited to fleeces or needle felts. Nevertheless, it has already been possible to produce textile semi-finished products for SMC applications based on hemp fibre bundles from the disordered fibre line. These were successfully processed into exterior bus applications and used in practical tests [1]. The latest studies show the potential of hemp and state essential steps along the value chain to ensure that hemp achieves the same level of development in the composites sector as flax [2, 3]. Thermoplastic matrices are excluded due to different industrial practices, compared to thermoset composites, and limited scientific literature regarding the influence of moisture on flax fibre reinforced thermoplastic composites. Nevertheless, the available scientific literature on hemp fibres and thermoplastic matrices are included in the literature review, section 2.

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OUTDOOR APPLICATIONS: A MARKET REALITY

Application 1: Left: Flax fibres composite bicycle bridge Ritsumasyl, The Netherlands - Inaugurated in 2020 ©Province of Friesland

Application 2: Gwalaz flax reinforced trimaran sailing since 2013 - ©Kairos

Application 3: Large frontage flax reinforced panel encapsulating a screen mounted above the entrance of a local movie theater in Paris ©Multiplast

Application 4: Flax reinforced paddles. ©Melker of Sweden

Application 5: Surfboards shaped with Flax/GreenPowy 56 - ©Notox

Application 6: Parisian Morris column with a Flax composites roof developed by Mecelec Composites - Installed since 2019 - ©JCDecaux

DISCLAIMER

The guidelines and best practices provide an excellent basis for the design of flax and hemp fibre composites in humid environments. However, it is recommended to provide additional validation of the adopted parameters for structural components and composite parts subject to harsh environments, similarly to other engineering materials. Please do not hesitate to contact CELC's office, to refine the recommendations for your specific application.

1 BEST PRACTICE GUIDELINES TO COPE WITH THE MOISTURE SENSITIVITY OF THERMOSET MATRIXES (MAINLY POLYESTER AND EPOXY) REINFORCED WITH FLAX FIBRES

All materials, and hence also all composite materials, are to some extent influenced by environmental factors like moisture, temperature, UV radiation, and the presence of chemicals and micro-organisms. The importance of these factors is dependent on the material and the precautionary measures taken. Indeed, while metals are sensitive to corrosion, the moisture sensitivity of flax fibre composites is a point of attention in certain applications.

1.1. GENERAL GUIDELINES

STATEMENT 1:

Control the moisture content of the flax fibre preform before composite production

The presence of moisture during composite manufacturing is of concern for all composites (natural, synthetic and mineral) and the **critical moisture content** of the preform or filler is dependent on the matrix. Resins with high, intermediate and low moisture sensitivity can be distinguished:

- High: e.g. polyurethane resin and polyesters with cobalt accelerators => drying of the preform is necessary.
- Intermediate: e.g. general epoxy resin => mild drying step could suffice since a limited amount of moisture can be tolerated.
- Low: e.g. polyester with cobalt-free accelerators and moisture tolerant epoxy resin => drying of preform not required, however, the use of non-dry fibres has implication on the manufacturing process, explained in next paragraph.

Hence, it is not always necessary to dry flax fibres before production. Moreover, recent research has shown that the durability of bio-composites upon repeated wetting and drying (swelling and shrinking) significantly benefits from not drying the fibres; the dimensional variation of non-dried (damp) fibres during moisture cycling is limited leading to reduced damage development. The composite manufacturing process should be adapted to allow processing with non-dried (damp) fibres:

- The preform can be conditioned in the production environment provided that the environment's humidity matches the standard indoor conditions; RH 30-60%
- Ideally, the flax fibre preform is conditioned at the relative humidity equal to the environmental humidity at which the composite part is exposed to in the use-phase. When the part is exposed to variable environmental humidity, like the outdoor climate, it is recommended to condition the fibres at the lower humidity range, e.g. 65% RH in case of the outdoor climate.
- Excessive moisture evaporation should be avoided during resin impregnation and curing since this can lead to porosity and reduced composite performance. Note that, when flax fibres are conditioned below 70% RH, the absorbed moisture is largely bound to the fibres and will not be so easily evaporated during processing when compared to the evaporation of liquid water. Nevertheless, a conservative practical guideline can be found based on the boiling point of liquid water. In other words, the peak curing temperature should be below the boiling point of water at the adopted processing pressure (e.g. below 100°C at 1atm, below 45°C at 0.1 bar, and below 180°C at 10 bar).
- When the manufacturing protocol cannot be adapted for the use of non-dried (damp) fibres, it is recommended to dry the fibres

When the fibres are dried before production, e.g. when working with moisture-sensitive resins, keep in mind that moisturisation of the fibre occurs rapidly; hence, **the time between drying, and composite manufacturing should be limited** < 30 min - 2h depending on the areal weight of the preform and the number of layers. If the time between conditioning or drying and resin infusion exceeds this timeframe:

- The preform can be dried under vacuum in the mould, in case of a vacuum assisted manufacturing process.
- It is recommended to use moisture tolerant resins and a manufacturing process that avoids excessive evaporation of moisture.

STATEMENT 2:

Seal machined edges using a topcoat

Similarly as for glass and carbon fibre reinforced composites, machined edges should be sealed using a topcoat to prevent direct exposure of the fibres to their environment and to slow down moisture uptake. Standard composite coatings can be used since the matrix determines the type of topcoat. When this guideline is met, the influence of liquid water and high environmental humidity on flax fibre composites is not instantaneous and should be considered only after exposure during several days, weeks or even months. Therefore, peak moisture loads like periods of rain or short-term exposure to high environmental humidity can be neglected.

1.2. INDOOR CLIMATE OF BUILDINGS

STATEMENT 3:

When the general guidelines are met, no modification of the properties should be taken into consideration when used in the indoor climate

The average humidity and humidity fluctuations occurring in the indoor climate of residential buildings in Western Europe, or similar, are not likely to affect the properties of flax fibre composites.

1.3. OUTDOOR CLIMATE

STATEMENT 4:

Seal machined edges using a topcoat

Regardless of the fibre type (e.g. carbon, glass or flax), in outdoor applications, a topcoat is often applied over the entire composite part, inside and outside, to slow down moisture uptake and to protect the material from other environmental factors. As a result, the influence of moisture on the properties and surface quality of flax fibre composites can be reduced.

STATEMENT 5:

Take a stiffness reduction into account when designing and engineering flax fibre composites for outdoor applications

It is assumed that the moisture content in flax fibre composites will equilibrate with the seasonal humidity averages occurring in Western Europe, if machined edges, when present, are sealed. The moisture content alternates between the saturation level at relative humidities of 65 and 85%, corresponding to the average relative humidity in summer and winter respectively. This does not include outdoor applications where the composite is immersed or in continuous contact with water. Since adequate rigidity of the composite part should be guaranteed all year round, the part should be designed for the worst case scenario which is the winter average relative humidity of 85%.

To cope with the negative effect of moisture on composite stiffness, it is advised to consider a reduction of flax fibre stiffness by 15-50% compared with the datasheet values, as determined with IFBT (guidelines available from CELC) at standard conditions. However, recent research shows that it is feasible to limit the reduction of flax fibre stiffness to a maximum of 25%, corresponding to a (humidity related) safety factor of 0.75.

The reduction of fibre stiffness can be translated to the influence on composite stiffness by adopting the rules of composite mechanics. Generally, the influence of humidity decreases with increasing dependency of the composite stiffness on the matrix properties, which are less influenced by moisture. Following this reasoning, composite stiffness is less influenced for fleece or needle-felt based (random mat) composites, and cross-ply and woven composites loaded in the +/- 45° direction.

In the Table below, the percentual reduction of composite stiffness (in 0° for UD's, in warp or weft direction for balanced weaves and machine direction for random mats) was determined for various fibre architectures and a fibre volume fraction (Vf) of 30-40%. It is assumed that the longitudinal and transverse fibre stiffness, and matrix stiffness at standard conditions are 60, 6, and 3 GPa, respectively, and that both the transverse fibre stiffness and matrix stiffness are not affected by humidity.

Fibre architecture	Composite stiffness reduction loaded in fibre direction	
	Feasible (recent research)	Maximum
UD (Vf = 40%)	**< 23 %**	46 %
Woven (Vf = 40%)	**< 20 %**	40 %
Random mat (Vf = 30%)	**< 14 %**	29 %

STATEMENT 6:

Composite strength is retained while failure strain increases with 20-60% at high humidity

Due to the absorption of moisture, the stiffness reduction of flax fibre composites is paired with an increase in failure strain from 1.5% at standard conditions up to 1.8 – 2.4% at 85% RH, while the strength is retained. The increased failure strain implies that the composite toughness improves at high humidity.

STATEMENT 7:

Consider the effect of moisture ageing on composite strength and failure strain

Consider the effect of ageing resulting from the long-term exposure to the variable outdoor climate, also called "moisture ageing". This is in addition to the "static" or immediate effects of high moisture content described in statements 5 and 6. Similarly to other fibre composites like glass and carbon, microscopic internal damage can accumulate over the years due to the continuous absorption and desorption of moisture. It is assumed that the moisture content in the composite varies between the saturation level at the summer and winter average relative humidity of 65 and 85% respectively and long-term exposure to liquid water is avoided. Although further research and more in-service experience are necessary, the authors' anticipate that the degradation of composite strength and failure strain due to this additional ageing effect, is in the range of 10-20% depending on the exposure time, while no additional stiffness reduction due to moisture ageing needs to be considered for flax fibre reinforced thermoset composites.

By applying a topcoat, the fluctuations in moisture content are suppressed, limiting the effect of moisture ageing on composite strength.

STATEMENT 8:

Moisture ageing can affect the appearance and surface quality

1.4. IMMERSED, CONTINUOUS CONTACT WITH LIQUID WATER

STATEMENT 9:

Special caution and additional measures are required for applications immersed or in continuous contact with liquid water

Please do not hesitate to contact CELC's office, for specific recommendations for your application:
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2 OVERVIEW OF INDUSTRIALLY RELEVANT LITERATURE REGARDING THE INFLUENCE OF MOISTURE ON FLAX AND HEMP FIBRE COMPOSITES

2.1 INDOOR CLIMATE OF BUILDINGS

ENVIRONMENTAL HUMIDITY

Generally, the moisture load is mild in the indoor climate of buildings. The average relative humidity is as low as 30% in winter, due to central heating, and up to 60% in summer. Fluctuations in humidity levels are generally limited to seasonal variations due to the moisture buffering effect of furniture and surrounding walls. Exceptionally, peak moisture loads might occur in the bathroom or other humid areas. The above statements are based on a study in residential buildings in Western Europe having different types of construction; however, they might be expanded to similar buildings in comparable geographical regions [4].

INFLUENCE OF MOISTURE ABSORPTION

Water vapour present in the air can affect the properties of flax and hemp fibre composites. However, the effects are more pronounced in the higher humidity range, relative humidity (RH) above 70%. Gager et al. [5] have studied the properties of commingled flax/polypropylene needle punched felts compressed to composites with a fibre volume fraction of 35% when saturated at various humidity levels. In other words, the moisture content in the composite is in equilibrium with the environment. Results in Figure 2 show that the effect on composite stiffness is minor in the indoor climate, RH 30 – 60%. Similar results were found for unidirectional flax and hemp fibre reinforced epoxy composites [6-9]. In general, the overall properties of flax and hemp fibre composites are stable within the humidity range of the indoor climate.

INFLUENCE OF PROLONGED EXPOSURE TO CLIMATE

In an indoor climate, the seasonal variations of average relative humidity between 30% in winter and 60% in summer lead to changes in the moisture content of flax and hemp fibre composites; in this more extended time period the moisture present in the air has time to diffuse through the matrix. Microscopic damage might develop over time due to consecutive swelling and shrinking of the fibres due to absorption and desorption of moisture, respectively [10, 11].

However, Figure 3 adapted from Réquilé et al. [7], shows that hygroscopic strain or thickness swelling for unidirectional hemp fibre reinforced epoxy composites is limited when the water activity ranges between 0.3 and 0.6, corresponding to RH 30 and 60% respectively. In other words, swelling and shrinking of the fibres are limited in the indoor humidity range. This specific moisture sorption behaviour, having low variation in moisture content and thus thickness swelling between RH 30 – 60%, is also shown for flax fibres and can be explained by the absence of moisture condensation in the pores and lumens which only occurs at high relative humidity [12, 13].

Based on this knowledge and assuming that exposed fibre ends are sealed as explained in the general guideline, it is expected that seasonal variations in humidity in the indoor climate have little influence on the damage development in flax and hemp fibre composites. Hence, the variations in humidity in the indoor climate will not influence composite properties over many years.

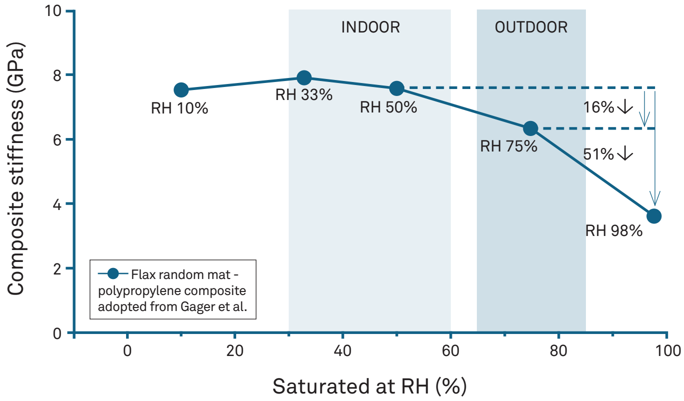

Figure 1: Data adapted from Gager et al. [5], the stiffness of commingled flax/polypropylene needle punched felts compressed to composites with a fibre volume fraction of 35% when conditioned until saturation at various relative humidity levels. The indoor area, in grey, ranges from the average relative humidity in winter to the summer average in residential buildings in Western Europe. The outdoor area, in grey, ranges from the average relative humidity in summer to the winter average in the Western European outdoor climate.

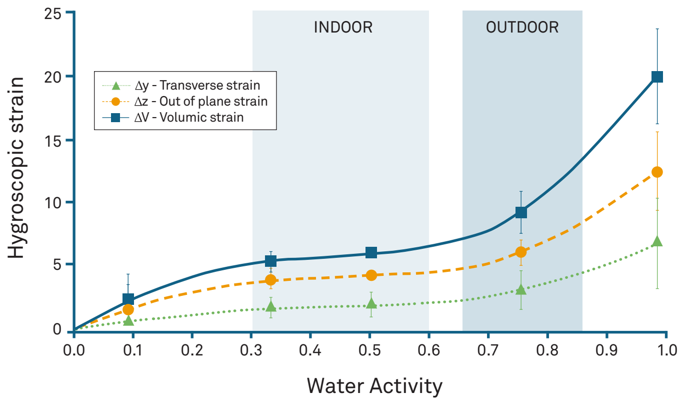

Figure 2: Figure adapted from Réquilé et al. [7], hygroscopic strain (%) in unidirectional hemp fibre reinforced epoxy composites conditioned until saturation in function of water activity. The indoor area ranges from the average relative humidity in winter to the summer average in residential buildings in Western Europe. The outdoor area ranges from the average relative humidity in summer to the winter average in the Western European outdoor climate.

2.2 OUTDOOR CLIMATE

ENVIRONMENTAL HUMIDITY

Based on the monthly humidity averages between 2010 – 2019 of weather stations across France, Germany, Switzerland and Belgium, the average humidity of the Western European outdoor climate is estimated at 85%RH in winter and 65%RH in summer. The fluctuations in humidity levels are more challenging to predict. There might be long periods of droughts and rain, and fluctuations in temperature will influence the speed of absorption. However, due to the generally slow moisture uptake of fibre reinforced polymer composites, it is assumed that the moisture content in the composite will largely follow the average seasonal humidity levels.

Recently, by monitoring the moisture content of flax fibre reinforced epoxy composites when exposed to the outdoor climate in Belgium, the composite materials group at KU Leuven evidenced that short-term exposure to peaks in relative humidity, and liquid water can indeed be neglected.

Outdoor applications where the composite is immersed or in continuous contact with water are excluded in the current analysis.

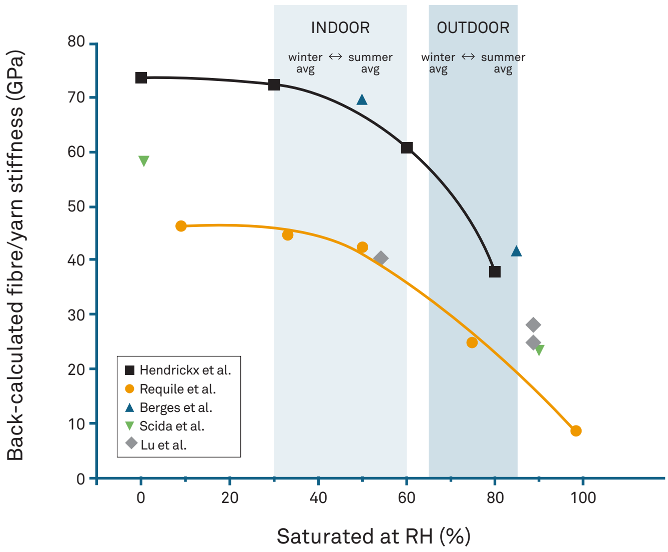

Figure 3: Literature overview on the relationship between stiffness and humidity. The rule of mixtures is adopted to back-calculate the fibre or yarn stiffness based on the published data. The reported values are obtained after conditioning until saturation at various humidity levels. Hendrickx et al. [6] studied unidirectional (UD) flax – epoxy composites, Requile et al. [7] evaluated UD hemp – epoxy composites, Berges et al. [8] and Scida et al. [9] both studied quasi-UD flax – epoxy composites, and Lu et al. [14] examined UD flax – polyester composites. The indoor area, in grey, ranges from the average relative humidity in winter to the summer average in residential buildings in Western Europe. The outdoor area, in grey, ranges from the average relative humidity in summer to the winter average in the Western European outdoor climate.

INFLUENCE OF MOISTURE ABSORPTION

As for many substances, the absorption of moisture by flax and hemp fibre composites leads to softening of the material. Typically, the failure strain increases with increasing moisture content while the stiffness or rigidity shows the opposite trend. Since adequate rigidity of the composite part should be guaranteed year-round, the part should be designed for the worst-case scenario which is the average relative humidity in winter of 85%. Below, literature data and recent results within the composite materials group of KU Leuven are discussed to quantify the direct influence of moisture absorption.

In Figure 4, a literature overview regarding the relationship between stiffness and humidity is given. The rule of mixtures was adopted to back-calculate the fibre or yarn stiffness based on the published data. Berges et al. [8] studied quasi unidirectional flax fibre - epoxy composites and reported a decrease in flax yarn stiffness of 40% when comparing the stiffness at 85% humidity with the value at standard conditions, RH 50%. In the study of Réquile et al. [7]on UD hemp – epoxy composites, the effect was even more pronounced as a decrease of 42% was already reached at a humidity level of 75%. Hendrickx et al. [6] and Scida et al. [9] used the oven-dry state as a reference condition and found a decline of 49% and 60% for flax fibre reinforced epoxy composites when tested at 80% and 90%RH respectively. While all the previous studies evaluated the tensile properties of fibre reinforced epoxy composites, Lu et al. [14] studied flexural properties of UD flax – polyester composites. Results showed a 35% reduction in fibre stiffness in the range between RH50 and RH89. Important to note is that the variation of examined humidity levels hinders comparison amongst literature. Indeed, the stiffness in oven-dry state is slightly higher than the datasheet value which is determined at standard conditions, 50%RH. In addition, the lack of datapoints at high humidity, where large variations are expected, hampers the correlation of data in this region. To sum up, the study specifically evaluating the desired humidity range, RH50 vs RH85, predicts a 40% reduction of flax fibre stiffness while comparable literature generally suggests a slightly stronger effect.

The decrease in stiffness at high humidity is paired with an increase in elongation while strength is retained. Berges et al. [8] reported an increase in failure strain of 60% compared with standard conditions, RH50%, when flax fibre reinforced epoxy composites were saturated at RH85%. This result is in line with other findings [5, 7, 9]. The increase in failure strain, resulting from the plasticising effect of moisture, implies that the composite toughness benefits from moisture sorption.

Recent studies of Moghimi et al. and Koolen et al. within the composite materials group of KU Leuven (yet to be published) suggest a milder influence of moisture uptake compared to previous studies in literature. Moghimi et al. investigated polyester composites reinforced with various (quasi) UD preforms from different manufacturers and compared the flexural properties at RH65 and RH85 with the value at standard conditions, RH54. Note that, like in the previous studies, the composites were exposed to the specified humidity until the moisture content in the composites was in equilibrium with their environment. Results, summarised in Figure 5, show a 15-25% reduction of back-calculated fibre/yarn stiffness at the winter average relative humidity, which is significantly lower than in previous studies. Variations in impregnation quality, composite porosity and method of conditioningare suggested as potential explanations. Elaboration of the differences within this dataset lies beyond the scope of this paper.

Koolen et al. (results yet to be published) examined both the effect of moisture absorption and prolonged moisture exposure on UD and cross-ply, CP, flaxepoxy laminates. The moisture content in the composites, having a fibre volume fraction of 30%, was varied between roughly 3.8 and 5.4% in a cyclic manner which approaches the saturation value at RH65 and RH85, respectively. The experiment was performed in a climate chamber at 40 °C and the specified moisture content was reached by 2 weeks of conditioning at RH65 and RH85 or 1 week at RH60 and RH90. Over a period of 10 months, the tensile and flexural properties were determined and the back-calculated fibre stiffness is shown in Figure 6. Results show a stronger reduction of bending stiffness, compared to pure tensile loading, meaning that compression properties are more sensitive to moisture. Since the long term effect of varying humidity on composite stiffness is negligible, as described in the following section, this study suggests that the average reduction in fibre stiffness is only 10% when the stiffness at the winter average relative humidity, RH85, is compared to the value at standard conditions, RH50. Results showed a 20% increase of failure strain, while the limited influence of moisture uptake on the static strength is in line with earlier findings.

Concluding, due to the variability in test conditions and results, literature regarding the stiffness reduction of flax and hemp fibre composites at high humidity is, for the time being, not conclusive. In addition, most studies are limited to UD or quasi UD reinforcements and an epoxy matrix. However, we have shown that the reduction of fibre stiffness in fibre direction at 85% RH is in the range of 15-50% for (quasi) UD flax and hemp fibre reinforced epoxy composites when compared to the value at standard conditions, 50%RH. Further research is necessary to narrow this range and to confirm the statement for other reinforcement types.

It might be possible to limit stiffness reduction by applying a gelcoat/ topcoat to slow down moisture ingress further. In this case, the moisture content in the composite part might equilibrate with the long-term humidity average, which is 75% in the Western European climate. As a result, the moisture content in the composite might not reach saturation at 85%RH, winter average, and the influence on the stiffness might be milder. Further research is required to confirm this statement.

INFLUENCE OF PROLONGED EXPOSURE TO CLIMATE

For the outdoor climate, the average humidity varies between 65% in summer and 85% in winter. Figure 3, adopted from Réquilé et al. [7], shows a strong increase of the composite hygroscopic strain when the water activity increases from 0.65 to 0.85, indicating that the fibres have significant dimensional changes between 65-85%RH. Consecutive swelling and shrinking of the fibres resulting from the seasonal variations in humidity are likely to cause microscopic damage over time, especially if no precautions are taken [10, 11]. As a result, various composite properties like strength, failure strain, impact and fatigue behaviour might be negatively affected since these properties are sensitive to internal damage.

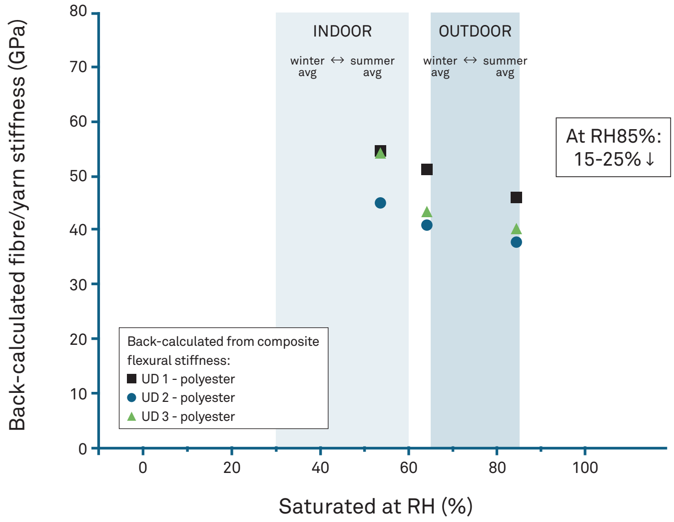

Figure 4: Moghimi et al. (yet to be published), recent results within the composite materials group KU Leuven, Belgium. The rule of mixtures is adopted to back-calculate the fibre or yarn stiffness based on the properties of (quasi) unidirectional flax fibre reinforced polyester composites. The reported values are obtained after conditioning until saturation at various humidity levels. The indoor area, in grey, ranges from the average relative humidity in winter to the summer average in residential buildings in Western Europe. The outdoor area, in grey, ranges from the average relative humidity in summer to the winter average in the Western European outdoor climate.

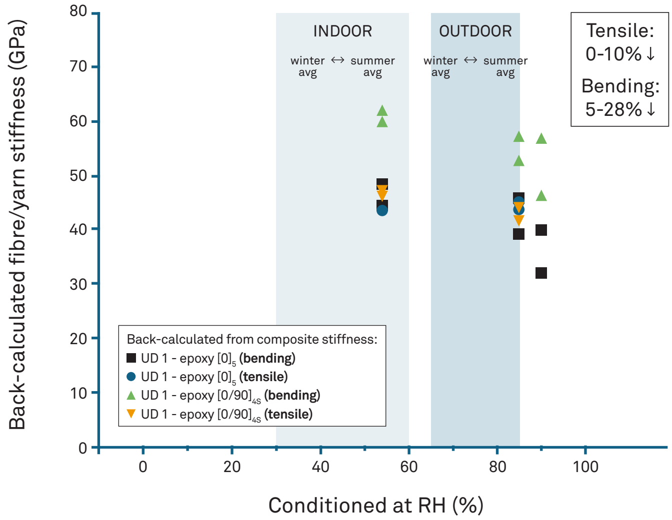

Figure 5: Koolen et al. (yet to be published), recent results within the composite materials group of KU Leuven, Belgium. The rule of mixtures is adopted to back-calculate the fibre stiffness based on the properties of unidirectional and cross-ply flax fibre reinforced epoxy composites. The averages of 5 samples, obtained at various testing moments, are reported during long-term exposure to variable relative humidity. The reported values are obtained after conditioning for 4 weeks at standard conditions, 23°C, 2 weeks at RH85, 40°C, and 1 week at RH90, 40°C. The indoor area, in grey, ranges from the average relative humidity in winter to the summer average in residential buildings in Western Europe. The outdoor area, in grey, ranges from the average relative humidity in summer to the winter average in the Western European outdoor climate.

Although various researchers have studied moisture ageing of flax and hemp fibre composites, it is currently not possible to establish a strong relationship between composite properties and exposure time to the Western European outdoor climate. Long term studies in similar ageing conditions are scarce, and the ageing process is often accelerated in a lab environment by using higher temperature or more extreme differences in relative humidity. Nevertheless, the available literature is examined to provide the first indication.

During a study of one year, Cadu et al. [15] subjected unidirectional flax fibre epoxy composites to 52 ageing cycles in a controlled lab environment. One cycle included 3.5 days of conditioning at both high humidity, RH90, and low humidity, RH40, at 55°C, and the composite properties were determined after reconditioning for 7 days at RH50%, 23°C. Results showed constant composite strength and failure strain in the first part of the ageing process, followed by a gradual decrease of 14 and 20% respectively. The stiffness was constant during the entire experiment, except for a small drop in an early stage which was assigned to a potential difference in moisture content or early damage formation. Unpublished results within the KU Leuven composites materials group showed similar behaviour when unidirectional flaxepoxy composites were subjected to 14 ageing cycles between RH 26% and RH78% at 80°C. In contrast to the previous study, the exposure time to both the wet and dry condition was 7 days which allowed the moisture content in the composites to equilibrate with their environment. In other words, there were fewer cycles but the difference in moisture content was larger which led to higher hygroscopic stresses. The composite strength and failure strain showed a linear decrease up to 19 and 22% after 14 cycles, respectively, while the stiffness was not significantly affected. Note that according to the authors' knowledge, the available literature is limited on the long term behaviour of thermoplastic composites when subjected to environmental humidity. The effect on composite strength and failure strain might be more profound as the compatibility and interfacial strength, which governs damage development during ageing, are typically lower in thermoplastic composites. However, this does not prevent the use of these materials in outdoor conditions which is proven in the Mercedes A-class where the rear cover is made with an abaca fibre reinforced polypropylene composite.

The moisture content in a composite part that is subjected to the Western European outdoor climate does not fluctuate with the same magnitude and pace compared with the accelerated lab experiments. Indeed, assuming that fibre ends are sealed as described in the general guideline, it is expected that the moisture content in the composite largely follows the seasonal averages and thus, one year in service might be linked with one wet-dry cycle between RH85 and RH65. Therefore, the anticipated long-term degradation of composite strength and failure strain is 10-20% when thermoset matrices are used, which strongly interact with flax and hemp fibres, e.g. epoxy systems. In contrast to the effect of moisture sorption, microscopic damage development, due to long-term exposure to the outdoor climate in Western Europe, does not have a significant influence on composite stiffness. Note that other environmental factors like temperature, UV radiation and micro-organisms might also play a role in an outdoor environment.

Several strategies can be applied to minimise the effect of moisture ageing. Firstly, a gelcoat/ topcoat can be applied to slow down moisture uptake, which is also adopted for traditional composites reinforced with glass and carbon fibre. Secondly, instead of drying the fibres before production, non-dried (damp) fibres can be used with a tailored production method [14, 16]. Finally, although more research is needed to apply these techniques on an industrial scale, several treatments can be performed to reduce the fibre hydrophilicity, and the fibre-matrix interphase can be improved to suppress damage development [10].

Lu et al. [17] showed that outdoor ageing most closely resembles a lab-scale immersion test when the fibre ends of flax fibre – polyester composites were not protected. Water immersion has a stronger effect on the stiffness and long-term behaviour of flax and hemp fibre composites than exposure to humidity in the air, which stresses the importance of sealing exposed fibre ends after machining and avoiding continuous contact with liquid water without additional precautionary measures. These types of applications will be elaborated in the future version of this document.

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ABOUT THE EUROPEAN CONFEDERATION OF FLAX AND HEMP | CELC

CELC is the only European agro-industrial organization federating all the stages of production and transformation for flax/ linen & hemp - 10 000 European companies in 14 countries -, leading this industry of excellence in a globalized context. This mission relies on the innovative and environmental values of these natural fibres, guaranteed by traceability labels EUROPEAN FLAX® and MASTERS OF LINEN®.

ABOUT 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 fibre composites.

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