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1 **Understanding the effect of hygroscopic cycling on the internal stress and stiffness** 2 **of natural fibre biocomposites**

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9 10 **Abstract**

11 This article investigates the development and the evolution of hygroscopic stresses within flax/
12 Polypropylene + Maleic Anhydride grafted Polypropylene (PP+MAPP) asymmetric biocomposites when
13 exposed to various hygroscopic cycles that simulate a wide range of outdoor applications with large
14 Relative Humidity (RH) variation (from 11 to 50% RH, 50-99% RH, 11-99% RH) and with various
15 cycling periods (1-week and 24-hour cycles between 50 and around 90% RH). The transversal and
16 longitudinal tensile properties of biocomposite laminates are characterised, and the weight and curvature
17 of the asymmetric samples are tracked throughout the cycles. The study shows that the hygroscopic
18 cycles entail a reduction of internal stress due to damage development and a relaxation mechanism that
19 are illustrated by permanent hygroscopic deformations. Two parameters have been identified to play a
20 role on the damage development: the magnitude of the RH level and the duration of the cycles.

21 **Keywords:** A Natural fibres; A Biocomposites; B Residual stress.

22 23 1. **Introduction**

24 Natural fibres, including flax fibres, are receiving increased attention in several sectors such as the
25 automotive [1] and marine industries [2], as they exhibit competitive tensile properties combined with
26 low density [3]. Moreover, they are more environmentally attractive than glass fibres as reinforcement for
27 composite materials [4]. However, their moisture-related performance is still not well understood, even
28 though it represents a major limitation to their industrial applicability. Reviewing the related literature
29 shows that most articles deal with their immersion in water and its consequences on mechanical

30 properties. Flax fibres can absorb moisture up to 20% of their mass at 99% relative humidity (RH) [5],
31 which brings their radial swelling up to more than 20% [6]. When they are embedded in a composite and
32 submitted to wet environments, hygroscopic stresses arise due to differential swelling between fibre and
33 matrix [7].

34 For the sake of clarity, residual stresses mostly refer to process-induced stresses [8–11], whereas internal
35 stresses are induced by environmental (moisture content [12], temperature [13]) or mechanical loading
36 [14, 15]. For a single flax fibre, the Coefficient of Hygroscopic Expansion (CHE) in the radial direction
37 has been estimated to be $\beta_T = 1.14 \text{ } \epsilon/\Delta C$ [6] and to lead to much superior strains than those induced by
38 their Coefficient of Thermal Expansion (CTE0 ($\alpha_{TT} = 83 \cdot 10^{-6} \text{ } \epsilon/^\circ C$ [16]). The axial direction undergoes
39 weak expansion due to the low cellulose microfibril angle in the S2 layer of flax fibres [17]. The
40 hygroscopic internal stresses can induce micro-cracking of the matrix [18], influence the moisture uptake
41 [19], and finally alter the mechanical performance [7, 20-21]. Some work has indicated that a
42 compressive state around the fibres may however enhance the load transfer properties [6]. It is thus
43 necessary to better understand the generation of hygroscopic stresses on a biocomposite system.

44 To this end, several authors [22,23] have shown that it is possible to estimate the transverse stress state of
45 $[0^\circ, 90^\circ, 0^\circ]$ symmetric laminates by measuring the curvature of a $[0^\circ, 90^\circ]$ asymmetric laminate of the
46 same material. Very few studies deal with natural fibre-reinforced biocomposites. Péron et al. [7, 12] have
47 used flax/PP+MAPP asymmetric laminates exposed to immersion or relative humidity and compared the
48 experimentally measured curvature with the numerically predicted one. This produced good agreement
49 that permitted the validation of the numerical model. These asymmetrical configurations can also be used
50 to develop new paradigmatic smart materials, i.e., shape-changing hygromorph biocomposites [24–29].

51 During their life cycle in outdoor applications, biocomposites are rarely exposed to a unique
52 environmental condition but may be subjected to environmental cycling. To the best of the authors’
53 knowledge, no available article deals with the impact of environmental cycling on the behaviour of
54 asymmetric biocomposites to better understand the evolution of the induced stress state.

55 All the available articles focus on symmetric biocomposites subjected to water immersion and drying
56 cycles [27, 30–34]. Some authors have used immersion and drying times as key variables for their
57 experiments (i.e., “transient” cycles) while others have waited for stabilization in the mass of their
58 samples (i.e., “saturation” cycles). A few studies have focused on the hygrothermal cycling of

59 biocomposites in water vapour environments [35-37]. Moreover, no clear justification has been proposed
60 for the selection of the hygroscopic conditions despite its necessity for the analysis of results.
61 Hence, the present article aims to fill the gap with regard to understanding the generation and evolution of
62 hygroscopic internal stresses in a biocomposite during hygroscopic cycles that simulate a wide range of
63 outdoor applications. The resulting typology and effects are discussed, and the establishment of an
64 original scenario is proposed.
65 For the study, asymmetric flax/PP+MAPP biocomposite stripes were manufactured by Vacuum-Bag-Only
66 (VBO) moulding, along with longitudinal and transversal tensile samples. The samples were exposed to
67 different hygroscopic cycles. First, “saturation” hygroscopic cycles were performed, where the change in
68 condition was triggered by the stabilization in weight of the samples achieved at 23 °C, under three
69 different environmental conditions. In parallel, “transient” hygroscopic cycles were applied with a cycling
70 period of 1-week cycles and 24-hour cycles. The moisture content and curvature of the asymmetric
71 samples were tracked along the hygroscopic cycles. In addition, the unidirectional samples gave access to
72 the hygroexpansion, tensile longitudinal and transversal stiffnesses of the biocomposites throughout the
73 cycles. Finally, an estimation of the stress state in an equivalent symmetric lay-up was calculated.

74

75 2. **Material and methods**

76 2.1. *Materials, manufacturing route, and samples used*

77 For the processing of the biocomposites, 50 g/m² unidirectional flax tapes were supplied by Linéo –
78 NatUp (Flaxtape FT50). According to the manufacturer, no physical or chemical treatment was carried
79 out on the fibres, which were harvested in France, dew retted, scutched, and hackled. Polypropylene (PP)
80 (Total Petrochemicals PPC 3660) and compatibilized PP with 4% Maleic Anhydride (MAPP) (Arkema
81 Orevac CA 100) were mixed and extruded as films.

82 The biocomposites were processed with film stacking and VBO moulding. FT50 tapes (12 plies) and
83 PP+MAPP films were stacked on an aluminium plate with a caul plate to reduce thickness variation.
84 Spacers were used to control the final thickness of the part. A draining fabric was settled around the lay-
85 up, and the vacuum-bag was then sealed. Based on a previous parametric study [2], the whole set up was
86 placed in an oven at 180°C during 45 min and vacuumed at 950 mbar. The fibre volume fraction was
87 targeted to be 40%. By controlling the number of polymer films, density measurement estimated a fibre

88 volume fraction of $42.2 \pm 1.5\%$. The densities of the PP+MAPP and related flax-reinforced biocomposites
89 were measured by immersion method in ethanol, as described in ISO 1183, on at least five samples of
90 each, using a Mettler Toledo MS-DNY-54 balance (accuracy 10^{-4} g). The density of the dried flax fibres
91 was measured with an AccuPyc II 1340 gas pycnometer from Micromeritics™, using helium. The density
92 of the matrices was found to be 0.90 ± 0.01 for the PP+MAPP and 1.14 ± 0.00 for the Epoxy resin. The
93 density of the dried flax fibres was 1.48 ± 0.02 .

94 Two thermocouples recording the temperatures during the process were placed in the centre of the oven
95 and in the middle of one stack. The thermal cycle applied in the oven was composed of a heating step at
96 $10^{\circ}\text{C}/\text{min}$, a plateau at the processing temperature, and a cooling step. The cooling rate was around
97 $1^{\circ}\text{C}/\text{min}$ due to the oven thermal inertia and air-cooling process.

98 The selected process enabled the manufacturing of thermoplastic composite parts with potentially large
99 dimensions and complex shapes. The materials were stored at 23°C , 50% RH several weeks before
100 processing until their weight was constant.

101 The $[0^{\circ}]_{12}$ unidirectional flax/PP+MAPP plates were processed and cut into 250mm-long and 15mm-wide
102 stripes for the longitudinal samples and 250mm-long and 25mm-wide stripes for the transversal tensile
103 samples, using a milling machine. Those samples were then equipped with $[\pm 45]_s$ glass/epoxy tabs as grip
104 areas. $[0^{\circ}_3; 90^{\circ}_9]$ asymmetric flax/PP+MAPP plates were processed and cut into 10 x 70mm stripes in
105 order to study the development of residual and internal stresses within the biocomposites [27]. This
106 stacking sequence was chosen to maximise the amplitude of curvature, using the Timoshenko equations
107 [13] for slender beam structures, such as described in [27].

108

109 2.2. Environmental conditions, “saturation” and “transient” hygroscopic cycles

110 A laboratory conditioned at 23°C , 50% RH was used for the conditioning of the materials prior to
111 processing and of the biocomposites prior to testing. These conditions of 23°C , 50% RH constitute the
112 reference state at which there is no environmental loading. To study the development and evolution of the
113 hygroscopic stresses through hygroscopic cycles, different types of cycles were examined, such as
114 schematised in Fig. 1.

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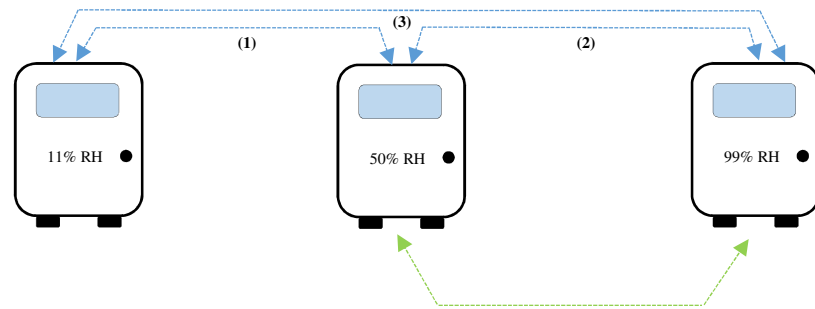
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Saturation cycles:

=> (1) Between 11% RH and 50% RH

=> (2) Between 50% RH and 99% RH

=> (3) Between 11% RH and 99% RH



Transient cycles:

=> 1 week (3.5 days at 50% RH and 3.5 days at 99% RH)

=> 24H (12H at 50% RH and 12H at 99% RH)

Fig. 1 – Schematisation of the various typologies of hygroscopic cycles examined in this work. Blue dotted lines: Hygroscopic cycles are achieved until saturation at 23°C between 11 and 50% RH, 50 and 99% RH, and 11 and 99% RH. Saturation times are variable. Green dotted lines: Transient hygroscopic cycles with fixed cycle periods are also examined: 1-week cycles between 50 (3.5 days) and 99% RH (3.5 days) and 24-hour cycles between 50 (12H) and 90% RH (12H). Moisture content is variable.

During the “saturation” cycles, the samples were conditioned in hermetic tanks at laboratory temperature at $23.2 \pm 2.2 \text{ }^\circ\text{C}$, in which the relative humidity was controlled using saturated salt solutions.

Throughout the different cycles, saturation was reached with a mean period of 12 days. The salts used were potassium hydroxide, magnesium nitrate, and potassium sulphate. Three different “saturation” cycles were examined in those tanks: between 11 and 50% RH, between 50 and 99% RH, and between 11 and 99% RH.

The environmental conditions (variation in time and RH) applied in this experiment did not follow any industrial standards where the humidity range is often prescribed. The purpose of the test was to bring fundamental information on the effect of the largest typologies of the humidity cycles (time and delta RH). In consequence, the results produced can be applied to a larger range of outdoor applications. In the literature, 50% RH is considered as the most well-established humidity condition used. In this regard, it is often included in the standard of mechanical characterization and enables better comparisons. The purpose of selecting 11 and 99% was to evaluate the effect of dry and wet environments that may be found in extreme outdoor environments. The salted solution induced the value of RH for a fixed temperature in order to evaluate the effect of the moisture content variation using the hypothesis of moisture being homogeneously distributed in the material. This hypothesis did not match practical outdoor applications where RH variation and consequently moisture variation are quicker and prevent

149 materials from reaching saturation. However, this choice constituted an ideal case deemed to facilitate
150 fundamental understanding of hygroscopic stress generation through calculations with reduced
151 uncertainties.

152 One batch of 7 asymmetric stripes, 12 longitudinal tensile and 12 transversal tensile samples was
153 assembled per cycling condition. The mass of the asymmetric stripes was measured daily for every
154 condition. When stabilization was reached after five weightings in the same range (i.e., five consecutive
155 values with no variation), the batches were moved to the next condition. Four longitudinal and four
156 transversal tensile samples were picked up after 1, 3, and 7 “saturation” cycles to be measured and tested.
157 Two “transient” cycles were examined, during which the period of cycling was kept constant. Samples
158 were exposed to 30 hygroscopic cycles in the hermetic tanks with saturated salt solutions between 50 and
159 99% RH with a cycling period of 1 week (3.5 days per condition). To study a shorter period of cycling, a
160 humidity chamber (Mettmert HCP) was used for practical reasons. A 24-hour cycle was achieved (12
161 hours per condition) between 50 and 90% RH, at 23°C, as 90% RH constitutes the limit of the machine.
162 A 24-hour transient cycle corresponds to moisture variation at the day level. The aim was to bring
163 information closer to outdoor applications. However, the results are more complex to interpret due to the
164 heterogeneous distribution of moisture within the sample and the additional stresses that it generates [12].
165 A 1-week cycle is considered as very close to the saturation cycle, which is finally the upper bound of the
166 transient cycles.

167 One batch of 7 asymmetric stripes, 15 longitudinal and 15 transversal samples was assembled per
168 “transient” cycling condition. At least three longitudinal and transversal tensile samples were picked up
169 after 3, 10, 21, and 30 cycles for the 1-week cycles, and 10, 25, 52, and 103 cycles for the 24-hour cycles.
170

171 2.3. Gravimetric measurements

172 The weighing was performed using a Mettler Toledo MS-DNY-54 balance (accuracy 10^{-4} g). The dry
173 mass of the flax/PP+ MAPP biocomposites was determined by drying a batch of five native samples with
174 vacuum at 105°C during 72 h [2, 39]. From that dry mass m_0 , supposing that the change in mass of the
175 samples was only due to the sorption of water by the biocomposites, the moisture content (%MC) was
176 tracked in the samples by weighing them, hence giving access to their mass m , using Equation 1:

$$177 \%MC = \frac{(m-m_0)}{m_0} * 100 \quad \text{Eq. 1}$$

178 The moisture content of the samples was calculated in the “saturation” cycles from the fifth stabilised
179 weight measurement in every condition, just before the tank switch. During the “transient” cycles, the
180 asymmetric samples were regularly picked up just before the switch in condition, and their weight and
181 curvature were measured.

182 2.4. Curvature measurements

183 The curvature of the asymmetric samples, as shown in Fig. 2b, was measured to access the development
184 of residual and internal hygroscopic stresses within the biocomposites. The inside outline of the bent
185 beams and samples was drawn on a paper sheet, scanned, and processed with the image analysis software
186 ImageJ® (National Institutes of Health, USA). A “circle fit” function can measure the bending curvature
187 (κ) of the samples, as shown in Fig. 2b. A null curvature $\kappa = 0$ corresponds to an infinite radius, and thus
188 to a flat sample. By convention, the curvature is considered negative $\kappa < 0$ when the sample is bent such
189 as the [90°] layer is inside the circle and positive $\kappa > 0$ when it is outside the circle.

190 The curvature of the samples at dry state was measured just after being removed from the oven. The
191 materials were considered dried, and the hypothesis was that the bending was induced only by the
192 residual thermal stresses induced by the manufacturing route. The samples were then stored until
193 stabilization at 23°C, 50% RH. The curvature measured at that point gave access to the sum of the
194 thermal and hygroscopic residual stresses in the material σ_R .

195 The curvature of the asymmetric samples exposed to “saturation” cycles was measured at stabilization in
196 every condition before the tank switch. The curvature of the asymmetric samples exposed to “transient”
197 cycles was measured regularly, as mentioned in the previous section, along with the weight measurement.

198

199 2.5. Tensile stiffness and swelling measurements

200 Mechanical tests were carried out to access the evolution of the longitudinal and transversal moduli of the
201 flax/PP+MAPP biocomposites across the cycles to calculate the transversal internal stresses across the
202 hygroscopic cycles. Mechanical tensile tests were performed in the laboratory at 23°C, 50% RH, in
203 accordance with ISO 527-5. The loading speed was 1 mm/min. The monotonic tensile tests were carried
204 out using an electromechanical MTS Criterion Model 42 test machine, fitted with a 5 kN load cell and an
205 MTS extensometer with a gauge length of 25 mm. For the longitudinal tests, the initial tensile modulus E_1
206 was calculated between 0.025% and 0.1% of strain and the second tensile modulus E_2 after 0.4% of strain,

207 as recommended in the literature [40]. For the transversal tests, the transversal modulus E_T was calculated
 208 from 0.05 to 0.25% of strain, as specified by ISO 527-1.

209 One set of 4 longitudinal and 4 transversal samples was tested without being exposed to any hygroscopic
 210 cycles after stabilization at 23°C, 50% RH. The tensile samples mentioned in section 2.2 were tested after
 211 being exposed to a certain number of hygroscopic cycles and after being conditioned until stabilization at
 212 23°C, 50% RH, for both “saturation” and “transient” cycles.

213 The dimensions of the longitudinal and transversal tensile samples were measured in the in-plane and out-
 214 of-plane directions using a Mitutoyo micrometre with a 10^{-3} mm accuracy. Those measurements were
 215 performed before any hygroscopic cycling, after stabilization at 23°C, 50% RH, and after the chosen
 216 number of cycles and stabilization at 23°C, 50% RH. These measurements were used to calculate the
 217 permanent swelling deformations in the longitudinal, transversal, and out-of-plane directions of the
 218 biocomposites, with Equation 2:

$$219 \quad \Delta x = \frac{(x - x_{BC})}{x_{BC}} \quad \text{Eq. 2}$$

220 x being a dimension measurement in a given direction and x_{BC} the measurement in the same direction
 221 before any cycle is done.

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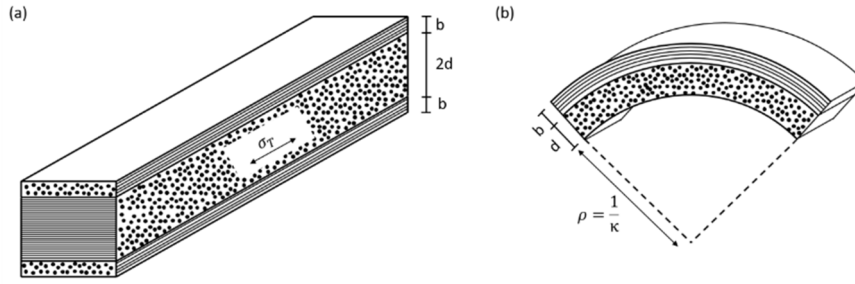
223 2.6. Calculation of the stress state in the equivalent symmetric lay-up

224 As mentioned earlier, and shown by several authors [9, 13, 22], it is possible to calculate the total stress
 225 state σ_{TOTAL} , which is the sum of residual and internal stresses of the $[90^\circ]$ layer of a $[0^\circ, 90^\circ, 0^\circ]$
 226 laminate, with the measurements of the curvature of an equivalent $[0^\circ, 90^\circ]$ laminate, made with similar
 227 materials, and knowing the longitudinal and transversal stiffness of the unidirectional composite. It is
 228 expressed in Equation 3:

$$229 \quad \sigma_{TOTAL} = -\frac{E_T E_1 k}{E_1 k + E_T h} \left(\frac{b+d}{2} + \frac{(E_1 b^3 + E_T d^3)}{6(b+d)} \left[\frac{1}{E_1 b} + \frac{1}{E_T d} \right] \right) * \kappa \quad \text{Eq. 3}$$

230 with E_1 and E_T representing respectively the longitudinal and transversal stiffness of the $[0^\circ]$ layer, k the
 231 thickness of both $[0^\circ]$ layers in the symmetric laminate, $2h$ the thickness of the $[90^\circ]$ layer, b and d
 232 respectively the thicknesses of the $[0^\circ]$ and $[90^\circ]$ layers in the asymmetric laminate, and κ the curvature
 233 of the composite such as described earlier. As shown in Fig. 2, in this work, k and h are respectively
 234 considered equal to b and d .

235



236

237 **Fig. 2 - Equivalent (a) [0°, 90°,0°] symmetric and (b) [0°, 90°] laminates (b and d are respectively the**
238 **thicknesses of the [0°] and [90°] plies).**

239 After calculating the residual stresses σ_{RES} based on post-processing conditions (i.e., dry state) it was
240 possible to evaluate the internal stresses across the cycles σ_{INT} , using Equation 4:

241
$$\sigma_{INT} = -\frac{E_T E_1 b}{E_1 b + E_T d} \left(\frac{b+d}{2} + \frac{(E_1 b^3 + E_T d^3)}{6(b+d)} \left[\frac{1}{E_1 b} + \frac{1}{E_T d} \right] \right) * \kappa - \sigma_{RES} \quad \text{Eq. 4}$$

242

243 2.7. SEM observations

244 To observe the development of the damage across the cycles, samples were embedded in epoxy resin and
245 polished with a 4000 abrasive sandpaper for observation under a Zeiss, EVO ® 40 scanning electron
246 microscope (SEM).

247

248 3. Results and discussion

249 3.1. Hygroscopic cycles in saturation conditions

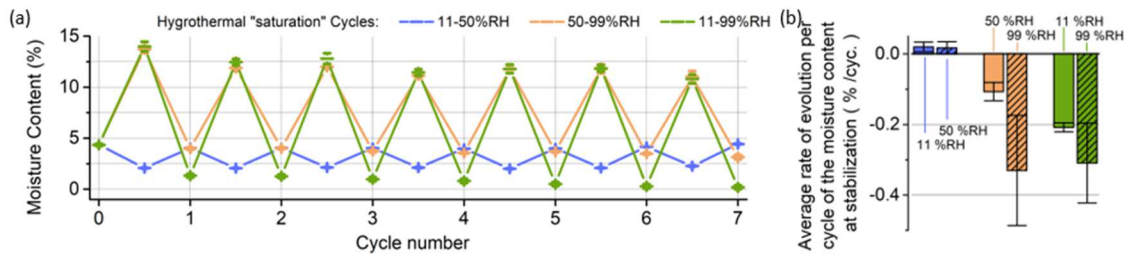
250 3.1.1 Moisture content evolution across the “saturation” cycles

251 The moisture contents at stabilization across the cycles of the flax/PP+MAPP biocomposite asymmetric
252 samples subjected to «saturation» cycles are presented in Fig. 3a and b.

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255



256

257 **Fig. 3 – (a) Moisture content of the flax/PP+MAPP asymmetric samples across the different “saturation”**
 258 **hygroscopic cycles. (b) Mean rate of evolution per cycle of the moisture content of the flax/PP+MAPP**
 259 **asymmetric samples across the different “saturation” hygroscopic cycles.**

260 The first point at the cycle N.0 corresponds to the stabilization of the samples at 23°C, 50% RH after

261 manufacturing. The initial moisture content is 4.10 ± 0.12 at 23°C, 50% RH, $2.12 \pm 0.05\%$ at 23°C, 11%

262 RH, and $13.74 \pm 0.16\%$ at 23°C, 99% RH.

263 Fig. 3b shows the rate of evolution of the moisture content at saturation for the flax/PP+MAPP samples

264 exposed to the different hygroscopic “saturation” cycles. We first note that the moisture content at

265 saturation of the flax/PP+MAPP samples exposed to hygroscopic cycles between 11 and 50% RH is

266 almost constant across the cycles. After seven cycles, the moisture content is 4.09 ± 0.16 at 50% RH and

267 2.10 ± 0.07 at 11% RH. The average moisture contents of the upper and lower boundaries are

268 respectively $2.11 \pm 0.07\%$ at 23 °C, 11% RH and $4.09 \pm 0.15\%$ at 23 °C, 50% RH.

269 Regarding the samples with larger hygroscopic amplitudes, i.e., “saturation” cycles between 50 and 99%

270 RH and between 11 and 99% RH, the moisture contents at saturation show a decrease across the cycles

271 (Fig. 3b). The final moisture content, after seven cycles between 50 and 99% RH, is $3.3 \pm 0.11 \%$ at 23°C,

272 50% RH and $11.60 \pm 0.16\%$ at 23 °C, 99% RH.

273 Samples exposed to larger cycles between 11 and 99% RH show a relatively greater decrease in both

274 boundary conditions than the samples exposed to cycles between 50 and 99% RH. The final moisture

275 content, after seven cycles between 11 and 99% RH, is close to zero at 23°C 11% RH, $2.71 \pm 0.10\%$ at

276 23°C, 50% RH and $11.52 \pm 0.17\%$ at 23 °C, 99% RH. Péron et al. [12] have shown that when a

277 biocomposite material is exposed successively to different environments, the greater the difference in

278 relative humidity between the two environments, the greater the transient internal stresses that the

279 material endures. Those stresses might be relaxed in the matrix, as shown by Newman et al. [33],

280 inducing the creation of a gap between the fibre and the matrix when the fibre shrinks again, and thus

281 accelerating the water damages.

282 Newman et al. [33], using epoxy/flax composites during 12 immersion/drying cycles, have shown that the
283 moisture content was slightly increased. Opposite results have been found by [17, 41, 42] where loss of
284 mass in immersion was observed during immersion/drying cycles and stated to be the result of soluble
285 polysaccharide leaching.

286 Nonetheless, the hygroscopic cycles examined here do not involve an immersion test, and the water is
287 present only in its vapour state. Cadu et al. [35] observed such a decrease in mass across hygroscopic
288 cycles and explained it as caused by hornification phenomena. When a certain level of water is removed
289 from the flax fibres, there is a microstructural change such as pore closure, and the hydrogen bonds that
290 link the polysaccharides together are broken and rebuilt within the molecules, inducing a loss of available
291 hydroxyl groups and thus a loss in hydrophilicity [43][44]. However, the decrease in mass is so important
292 that the samples exposed to cycles between 11 and 99% RH show a mass at stabilization at 11% RH at
293 the seventh cycle that is in the same order of magnitude as the dry mass of the samples, measured after
294 drying under vacuum at 105°C during 72 hours, close to 0%. Thus, hornification may not be the only
295 explanation for this observation.

296 This loss of dry mass during hygroscopic cycles may be explained by other mechanisms such as the
297 triggering of micro-organisms activity, such as bacteria and fungus, naturally existing in natural fibres
298 [45]. This point deserves to be further investigated elsewhere. As shown in Fig. 4, after 15 days of
299 exposition to 99% RH, fungal activity such as mold, whose growth might have consumed the organic
300 substract, appears at the surface of the flax/PP+MAPP samples.

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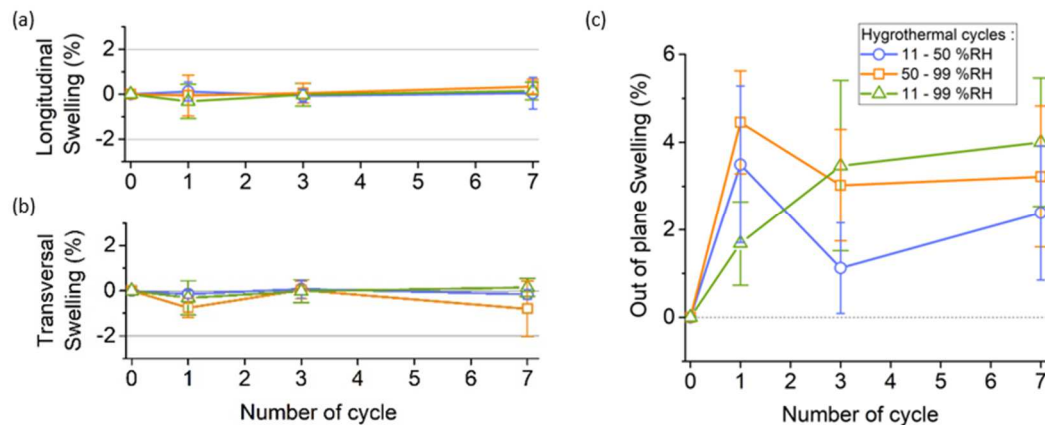
308 **Fig. 4 - Pictures of the surface of flax/PP+MAPP asymmetric samples after conditioning 15 days at 99 %RH.**
309 **The red circle highlights the appearance of mold.**
310

311

312 **3.1.2 Permanent out-of-plane swelling deformations across the “saturation” cycles**

313 The permanent hygroscopic deformations measured on the longitudinal and transversal samples across
314 the “saturation” hygroscopic cycles are presented in the in-plane longitudinal and transversal directions
315 and in the out-of-plane direction in Fig. 5a, b, and c, respectively.

316



317

318 **Fig. 5 – Permanent swelling in the (a) longitudinal, (b) transversal, and (c) out-of-plane direction of**
319 **flax/PP+MAPP biocomposite unidirectional samples across different “saturation” cycles.**

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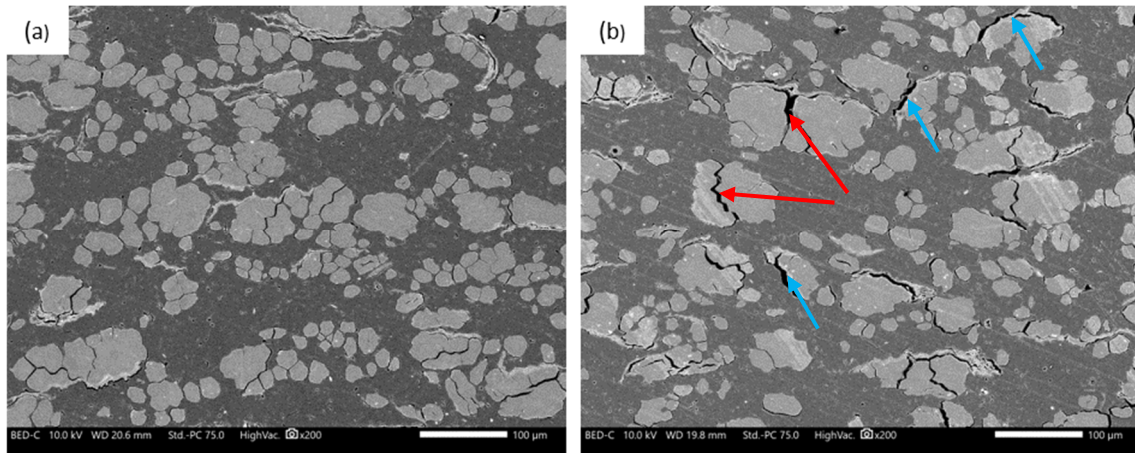
321 No permanent deformations are observed in the in-plane longitudinal and transversal directions across the
322 “saturation” cycles (Fig. 5a and b). Although the biocomposites are supposed to be transversally isotropic,
323 the swelling behaviour in the transversal and out-of-plane directions are very different (Fig. 5b and c).

324 This point is discussed elsewhere [46] and is proposed to be due to residual stresses implied by the
325 manufacturing route. The permanent deformations in the out-of-plane direction are in the same order of
326 magnitude, regardless of the “saturation” cycle the biocomposite samples were exposed to, around 3%.

327 Similar observations on flax/epoxy samples were made after one cycle of immersion until saturation [42].

328 The authors explained the trend by the stress release implied by molecular relaxation processes in the
329 matrix. As shown by the SEM observations in Fig. 6, cracks appear at the fibre/matrix interface and
330 fibre/fibre interface during the hygroscopic cycles. This is due to the shrunken fibres that pull away from
331 the matrix and from one another within the bundles.

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Fig. 6 - SEM observations of cross-sections of flax/PP+MAPP biocomposites laminates, (a) native and (b) after 15 "saturation" cycles between 50 and 99 %RH. Red arrows show intra-bundle cracks while blue arrows show interfacial cracks between fibre and matrix.

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Furthermore, the porosity content was observed to increase on flax/epoxy and flax/PP+MAPP composites with immersion cycles [27, 41]. As previously shown [2], the evolution of the porosity content is inversely proportional to the material density. Thus, out-of-plane swelling (Fig. 5) linked with a constant or decreasing mass (Fig. 3) results in a decrease in density. Therefore, it is possible to conclude that the porosity contents in the flax/PP+MAPP samples increase regardless of the "saturation" cycle the biocomposite samples were exposed to.

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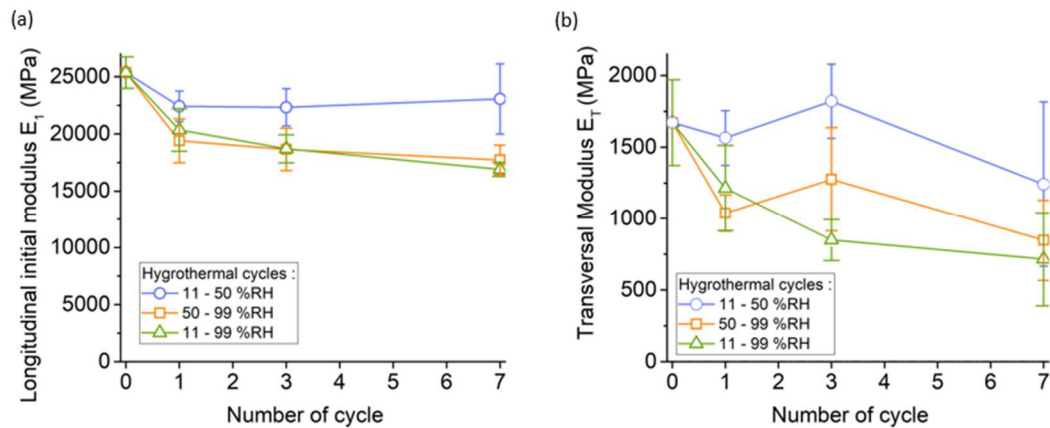
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3.1.3 Longitudinal and transversal stiffness across the "saturation" cycles

The flax/PP+MAPP biocomposite tensile samples tested after exposition to "saturation" cycles all showed typical non-linear behaviours in longitudinal and transversal directions, as described in [2]. No observable difference in behaviour was noticed during hygroscopic cycles. Fig. 7 shows the evolution of the longitudinal and transversal stiffness of the flax/PP+MAPP samples measured at stabilization at 23°C, 50% RH on unidirectional tensile samples that were previously exposed to different "saturation" hygroscopic cycles.



353

354 **Fig. 7 – Longitudinal stiffness E_1 and transversal stiffness E_T of the flax/PP+MAPP unidirectional**
 355 **biocomposites measured at 23°C, 50% RH, after exposition to the “saturation” hygroscopic cycles.**

356

357 A decrease in stiffness is observed in both directions for every sample exposed to “saturation”
 358 hygroscopic cycles. However, the decay in stiffness for the samples exposed to the hygroscopic cycles
 359 between 11 and 50% RH is lower than in the other conditions. After seven “saturation” cycles between 11
 360 and 50 RH, which represents about 6 months of cycling, an encouraging drop of only 9% is observed in
 361 longitudinal stiffness and 26% in transversal stiffness.

362 Such constancy in dry conditions is not observed when the samples are cycled at higher relative humidity.
 363 Samples exposed to “saturation” hygroscopic cycles between 50 and 99% RH and between 11 and 99%
 364 RH show decay in longitudinal and transversal stiffness, in the same order of magnitude, with
 365 respectively about 30% and 50% of decay. Decays in mechanical characteristics were already observed
 366 on flax/epoxy unidirectional biocomposites with 47% V_f exposed to “transient” hygroscopic cycles at
 367 55°C, between 40 and 90% RH in both longitudinal [35] and transversal directions [36], with respectively
 368 10% and 50%. The trend observed by the authors is slightly different due to the transient state of moisture
 369 content within their sample, the lower initial porosity content ($V_p = 2.5\%$ against $1.9 < V_p < 8\%$ here [2])
 370 and the epoxy matrix that allows better interfacial shear strength with flax fibres than PP+MAPP.

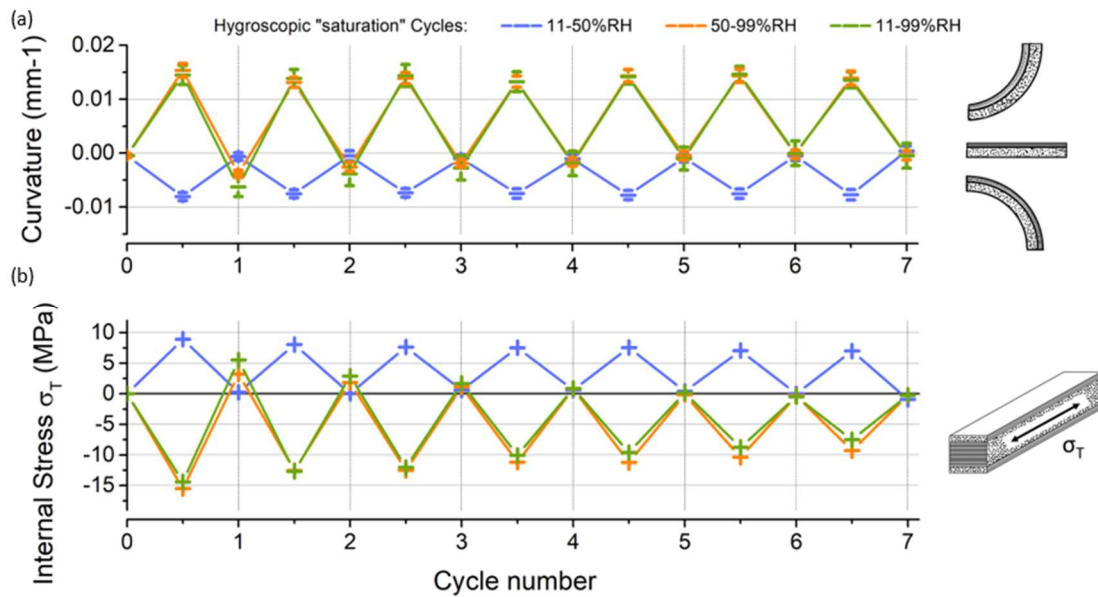
371 **3.1.4 Curvature at stabilization across the “saturation” cycles and calculation of the stress state**

372 During the process of VBO moulding, when the matrix is melted around the flax fibres, just before the
 373 cooling sequence, the flax fibres are totally dried [2], and the material is free of any stress [8]. Once the
 374 melting temperature is passed, the matrix solidifies around the fibres, and because of their different
 375 Coefficient of Thermal Expansion, the unidirectional plies shrink in the transversal and the out-of-plane

376 directions mostly. Thermal residual stresses develop at the laminate scale for laminate biocomposites, and
377 the asymmetric samples bend once demoulded, with the transversal direction inside. The curvature of the
378 asymmetric flax/PP+MAPP samples at dry state is measured at $-1.2 \cdot 10^{-2} \pm 0.1 \cdot 10^{-2} \text{ mm}^{-1}$. It has been
379 shown that the stiffness of biocomposites is sensitive to their moisture content [17]. However, in the first
380 approximation, the stiffness in longitudinal and transversal directions of the flax/PP+MAPP samples
381 examined is considered equal to those measured at 23°C, 50% RH. With the hypothesis that the curvature
382 at dry state is attributable only to the residual thermal stresses, Eq. 3 enables calculating the latter in the
383 transversal direction of the equivalent symmetric laminate [90°] layer at 12.9 MPa. This stress is induced
384 by the transversal shrinking that is restrained by the longitudinal layer. This value is higher than the
385 tensile transversal strength of the composites, measured at 8.9 MPa in a previous work on similar
386 material but with differently shaped samples [2]. It may be a source of irreversible damage, such as found
387 in the SEM observations shown in Fig. 6.

388 Once exposed to a humid environment, the flax fibres start to swell, while the PP+MAPP matrix is
389 relatively insensitive to the presence of water. The swelling of the fibres induces the expansion of the
390 unidirectional ply, mainly in the transversal and out-of-plane direction, because of the anisotropy of the
391 flax fibres. The swelling of the transversal plies induces a bending of the samples with the transversal ply
392 on the outside. After stabilization at reference state at 23°C, 50% RH, before cycling, the curvature of the
393 asymmetric samples is measured at $-4.5 \cdot 10^{-4} \pm 3.8 \cdot 10^{-5} \text{ mm}^{-1}$, which leads to the estimation of the
394 residual stresses at $\sigma_R = 0.5 \text{ MPa}$. This shows that the hygroscopic residual stresses (considering that the
395 sorption up to 50% RH is included in the process) at the reference state almost offset the residual thermal
396 stresses, inducing a null bending moment.

397 Fig. 8a presents the curvature at stabilization at the different cycling conditions κ , for the biocomposite
398 samples exposed to “saturation” hygroscopic cycles at 23°C, between 11-50% RH, 50-99% RH and
399 between 11-99% RH, across the first seven cycles.



400

401 **Fig. 8 - (a) Curvatures at stabilization of the flax/PP+MAPP asymmetric biocomposite samples across the**
 402 **“saturation” hygroscopic cycles. (b) Internal stress calculated in the equivalent symmetric laminate [90°] layer**
 403 **across the cycles for the flax/PP+MAPP asymmetric biocomposites exposed to “saturation” cycles.**

404

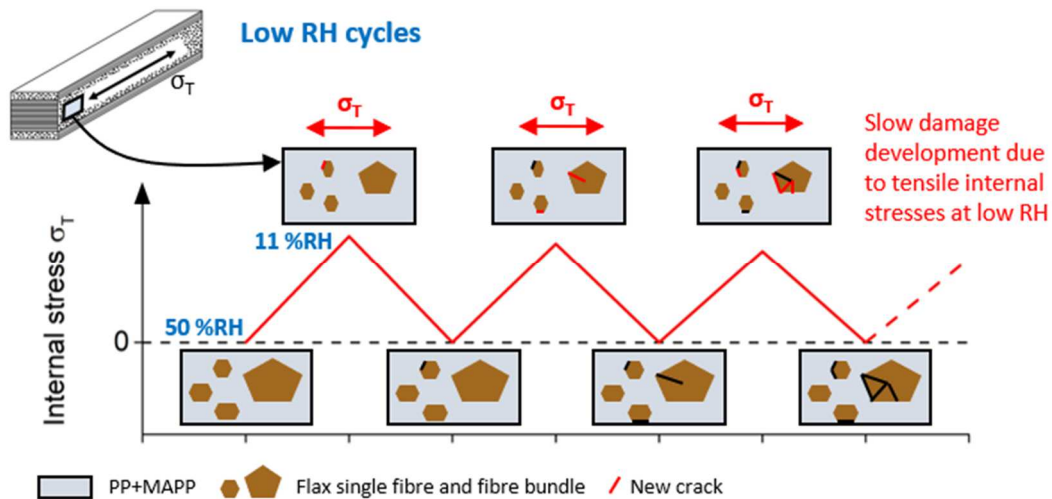
405 From these curvatures and linear regressions of the longitudinal and transversal moduli across the
 406 cycles(see the Appendix), it is possible to calculate the internal hygroscopic stresses in the equivalent
 407 symmetric laminate across the cycles, as shown in Fig. 8b. This is done using Eq. 4 and the hypothesis
 408 that the moduli at a given cycle are the same at stabilization at 11, 50 and 99% RH.

409 This is explained by the swelling in the transversal direction restrained by the [0°] layer, as was also
 410 shown by Péron et al. [12]. In the samples subjected to cycles between 11 and 50% RH, internal stresses
 411 remain close to 0 MPa at saturation at 50% RH. Internal stresses at saturation at 11% RH decrease from
 412 8.9 MPa to 6.1 MPa across the seven cycles. These stresses remain in the same order of magnitude as the
 413 transversal strength, as mentioned before, which may explain the permanent out-of-plane deformations
 414 developed across the cycles.

415 Regarding the samples exposed to cycles between 50 and 99% RH and after one stabilization at 99% RH,
 416 the internal stress in the [90°] ply at 50% RH is tensile and calculated at 3.3 MPa, whereas it was
 417 expected to be close to 0 MPa, such as in the case of the cycles between 11 and 50% RH. This
 418 overreaction of the internal stress response is also observed in the negative curvature of the samples back
 419 at 50% RH, and in the literature on flax/PP+MAPP asymmetric laminates [17] and on wood bilayers [47].

420 The tensile internal stresses calculated in the cycles from 50 and 99% RH and 11 to 99% RH are reduced
 421 over the seven cycles, respectively from 3.3 to -0.3 MPa and from 5.5 to -0.8 MPa. Regarding the
 422 compressive stresses at saturation at high moisture content for the cycles between 50 and 99% RH and
 423 from 11 to 99% RH, they also exhibit a reduction, respectively from -15.5 to -9.1 MPa and from -14.4
 424 to -6.2 MPa (Fig. 8).

425 When the biocomposites are successively exposed to low relative humidity, their transversal directions
 426 are exposed to cycled tensile internal stresses. Those successive internal tensile stresses induce
 427 progressive damage in the material, shown by the slight reduction of the mechanical properties (Fig. 7a
 428 and b) and the increase of the permanent out-of-plane direction (Fig. 5a, b and c), as schematized in Fig.
 429 9. Those phenomena induce relaxation of the internal hygroscopic stresses across the cycles.

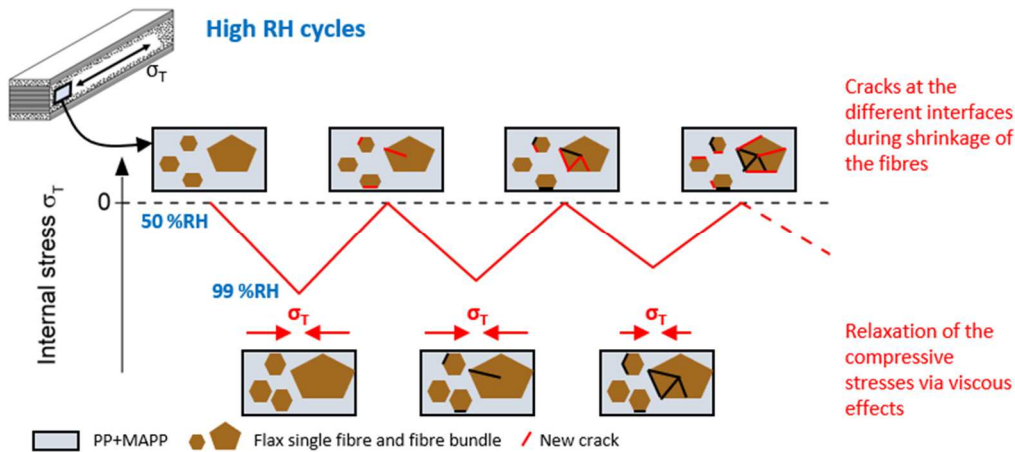


430

431 **Fig. 9 – Internal stress evolution during successive low RH exposure.**

432

433 When the samples are exposed to cycles with higher relative humidity, modification of moisture content,
 434 reduction of tensile properties, permanent out-of-plane expansion, and change of curvature are shown to
 435 be more drastic. Several authors have already shown the effect of swollen flax fibres at high moisture
 436 content, promoting irreversible damage such as plastic thresholds overreached in the matrix, leading to
 437 micro-cracks [30], cracks within the fibres [32], or viscous relaxation of the stresses within the matrix
 438 [33], the fibres, or at the different interfaces (cell-wall, fibre/fibre, and fibre/matrix), as schematized in
 439 Fig. 10.



440

441

Fig. 10 – Internal stress evolution during successive high RH exposure.

442

443 In addition, asymmetric lay-up curvature evolutions during hygroscopic cycles have all shown a reduction
 444 through a relaxation process of internal stresses, which is a function of the moisture content gradient.

445 Therefore, a larger moisture content gradient implies a larger relaxation through the plastic matrix
 446 deformation in the interface area.

447

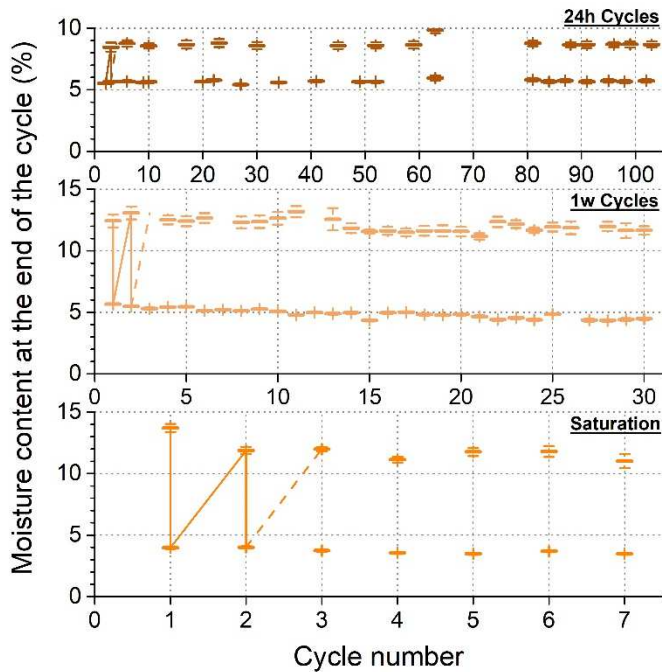
448 3.2. “Transient” hygroscopic cycles

449 3.2.1 Moisture content across the “transient” cycles

450 The moisture contents at the end of the cycles of the flax/PP+MAPP samples subjected to “transient”
 451 cycles between 50 and 90% RH with a 24-hour period of cycling and with a 1-week period of cycling are
 452 presented in Fig. 11. For comparison, the results from the "saturation" cycles between 50 and 99% RH are
 453 also presented in Fig. 11.

454 The moisture content reached at 99% RH by the samples exposed to 1-week cycles is in the same range as
 455 the “saturation” samples at the same relative humidity. This shows that after 3.5 days of exposure at 99%
 456 RH, saturation is almost reached.

457



458

459 **Fig. 11 – Mass measurements for the flax/PP+MAPP samples across the different “transient” hygroscopic**
 460 **cycles. 103x 24-hour cycles, 30x 1-week cycles, and 7x “saturation” cycles between 50 and 90% RH are presented.**

461

462 A decrease in mass is observed at the end of the cycles at either 50 or 99% RH. In contrast, the moisture
 463 content of the samples exposed to 1-week cycles at 50% RH evolves from 5.7% to 4.3%, whereas during
 464 the “saturation” cycles, the moisture content evolves between 4.0 and 3.5%. This shows the hysteretic
 465 sorption/desorption process with the desorption mechanisms being slower than the sorption mechanisms.

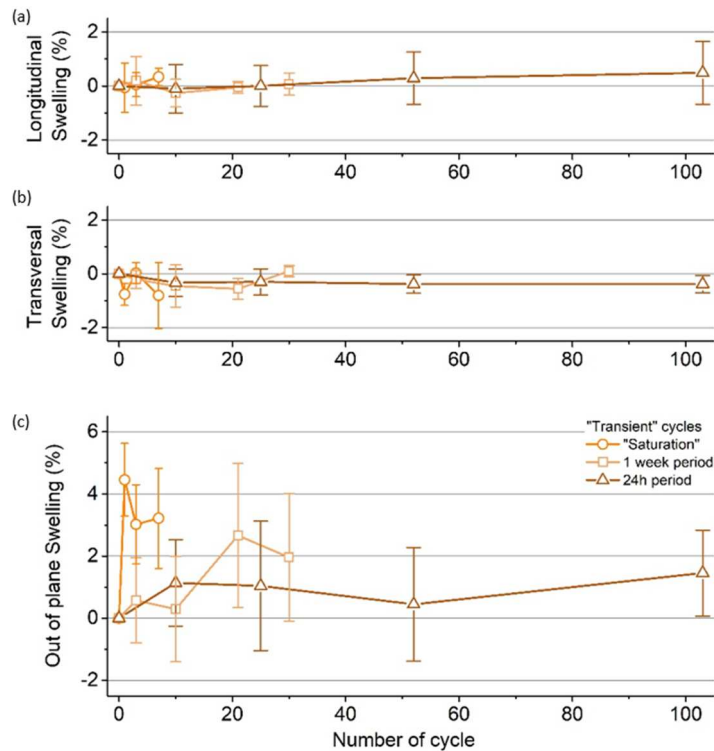
466 Using thermodynamic considerations and simulation, Chen et al. [48] have explained that cellulose-
 467 hydrogen bonds are associated with strong energy. Therefore, the cellulose-cellulose hydrogen bonds
 468 present in the dry material do not reform at the same % RH and breaks once the material is wet.

469 Regarding the samples exposed to 24-hour cycles, the moisture content for either 50 or 90% RH never
 470 reaches those of the “saturation” cycles. At 50% RH, this confirms the transient state of the biocomposite
 471 sorption, i.e., the presence of moisture gradients, which potentially induce internal stresses within the
 472 biocomposite [12].

473 The samples exposed to 24-hour cycles exhibit moisture contents at the end of the cycles that are constant
 474 over more than 100 cycles. At the same time, a decrease in mass is recorded for the 1-week cycles, in a
 475 lower magnitude than for the saturation cycles. This shows that the activity of microorganisms (Fig. 4)
 476 might be triggered by exposure to the high moisture content and is time-dependent.

477 **3.2.2 Permanent deformations across the “transient” cycles**

478 Fig. 12a, b, and c shows the longitudinal, transversal, and out-of-plane permanent deformations across the
479 cycles for the samples exposed to 24-hour and 1-week “transient” cycles, along with those of the samples
480 exposed to “saturation” cycles between 50 and 99% RH. As for the “saturation” cycles, no permanent
481 deformation occurs in longitudinal or transversal directions across the “transient” cycles.
482



483

484 **Fig. 12 – Permanent swelling in the longitudinal (a), transversal (b), and out-of-plane (c) directions of**
485 **flax/PP+MAPP biocomposite unidirectional samples across different “transient” cycles**

486 In the out-of-plane direction, “saturation” cycles induce around 3% permanent deformation against
487 around 2% for 1-week cycles and between 1.5 and 2% for 24-hour cycles. This confirms that the
488 “transient” cycles may be less damaging than the “saturation” cycles and that the cycling methodology is
489 important to qualify the durability of biocomposites. Moreover, permanent deformations, related stress
490 states, and potential damage are observed in the out-of-plane direction, regardless of the type of
491 hygroscopic cycles tested. This is due to the development of internal damage, such as cracks at fibre
492 bundle/matrix and single fibre/single fibre interfaces within the bundles (Fig. 6). This is, therefore, a key
493 mechanism that contributes to the durability of biocomposites against hygroscopic cycles.

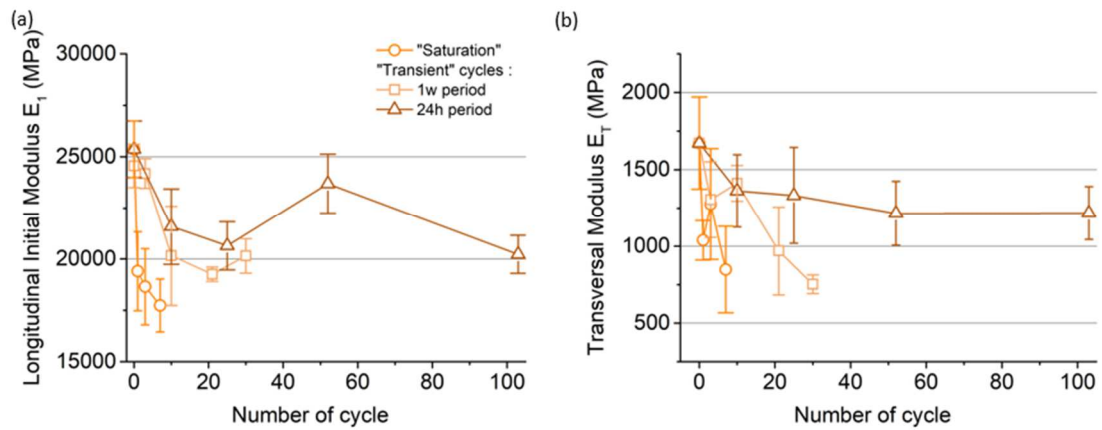
494 Nonetheless, it needs to be kept in mind that permanent deformations are measured throughout the whole
495 thickness, which gives an overall picture of the damage to the materials. During the “transient” cycles,
496 materials are submitted to local moisture content gradients that induce internal stresses even in the core of
497 the material. The localisation of the damage is not observable in the present case.
498 As explained in section 3.1.2, the increase of out-of-plane permanent deformations is linked to an
499 increase of the material volume, reduction of density, and thus porosity content. The samples exposed to
500 24-hour cycles are subjected to these phenomena in a lower order of magnitude than those exposed to 1-
501 week cycles.

502 *3.2.3 Longitudinal and transversal stiffness across the “transient” cycles*

503 After exposition to “transient” cycles, biocomposites all show a typical non-linear behaviour in
504 longitudinal directions that is not altered by cycling (not shown here). Fig. 13a and b shows the evolution
505 of the longitudinal and transversal stiffnesses of the flax/PP+MAPP samples measured at stabilization at
506 23°C, 50% RH on unidirectional tensile samples that were previously exposed to different “transient”
507 hygroscopic cycles. “Saturation” results from the hygroscopic cycles between 50 and 99% RH are
508 presented for comparison.

509 The longitudinal stiffness exhibits a drop of about 20% within 100 cycles for the 24-hour duration and the
510 30 cycles of 1-week duration. “Saturation” cycles lead to a more significant decrease in longitudinal
511 stiffness, with 32% along the seven cycles. A drop of 55% of transversal stiffness is observed within 30
512 1-week cycles vs. 27% within 100 24-hour cycles. For saturation cycles, the decrease in transversal
513 stiffness is in the same order of magnitude as that of the samples exposed to 1-week cycles. However, it is
514 reached after a fewer number of cycles.

515



516

517 **Fig. 13 – a) Longitudinal stiffness E_1 and b) transversal stiffness E_T of the flax/PP+MAPP unidirectional**
 518 **biocomposites measured at 23°C, 50% RH, after exposition to the “transient” hygroscopic cycles.**

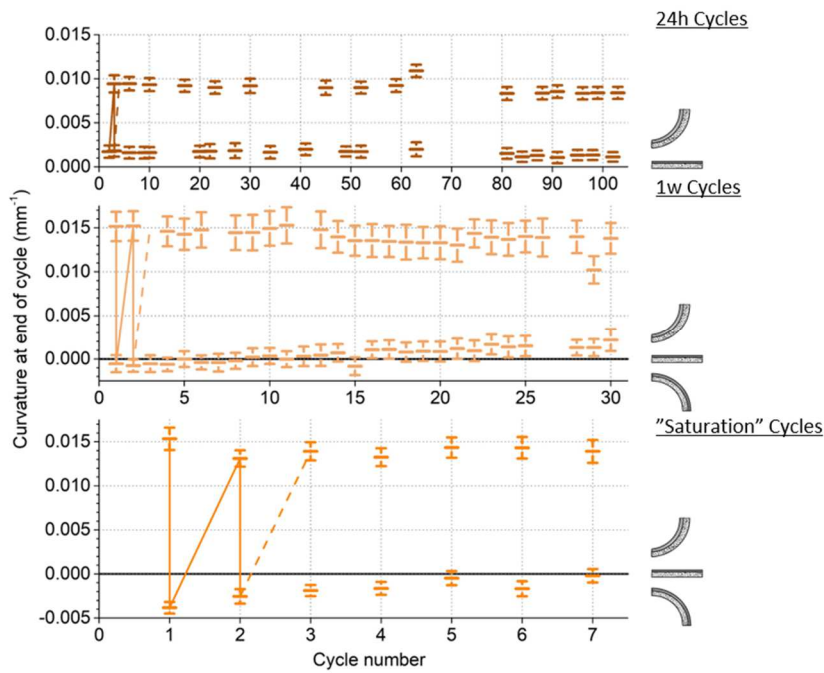
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520 The duration of the cycles, the moisture sorption reached, and the time spent at high moisture contents are
 521 key parameters to the process of damaging biocomposite samples and lowering their mechanical
 522 properties.

523 **3.2.4 Curvature across the “transient” cycles and approximation of the internal stresses reached**

524

525 Fig. 14 shows the curvature at the end of cycles for the different cycling conditions of the flax/PP+MAPP
 526 asymmetric samples exposed to “transient” hygroscopic cycles. Regarding the curvature across the 24-
 527 hour cycles and the curvature at 99% RH at the end of the 1-week cycles, a slight decrease is recorded.

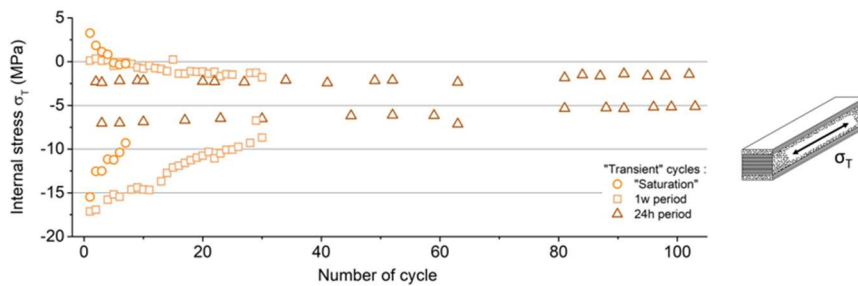


528

529 **Fig. 14 – Curvatures at stabilization of the flax/PP+MAPP asymmetric biocomposite samples across the**
 530 **“transient” hygroscopic cycles.**

531

532 As previously done, transversal internal stresses are approximated during the hygroscopic cycles by
 533 keeping a constant variation of stiffness with moisture. Only the evolution of the stiffness with the
 534 number of cycles is taken into account. It should be kept in mind that another approximation is made here
 535 that the internal hygroscopic stresses are homogeneous across the composite thickness. The results of
 536 these calculations are presented in Fig. 15.



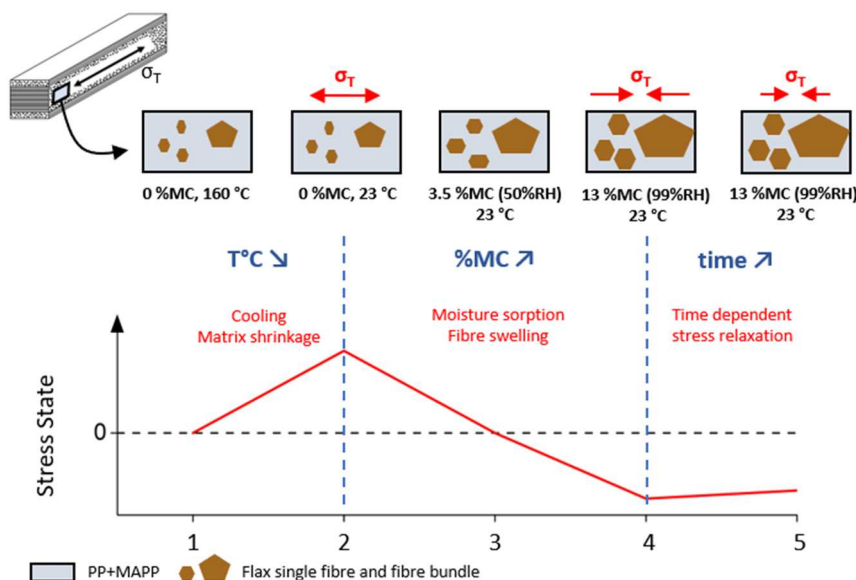
537

538 **Fig. 15 – Curvatures at stabilization of the flax/PP+MAPP asymmetric biocomposite samples across the**
 539 **“transient” hygroscopic cycles.**

540

541 Even though the samples exposed to 24-hour cycles are periodically exposed to 90% RH, the reduction of
 542 their internal stresses is low compared to longer cycling periods. Approximated compressive stress

543 decreases from -7.0 to -5.1 MPa after 100 cycles at 90% RH, and from -2.3 to -1.4 MPa at 50% RH.
 544 In addition, the overshoot of curvature observed for the “saturation” cycles between 99 and 50% RH is
 545 not observed on the 24-hour nor on the 1-week cycles.
 546 Relaxation is a time-dependent mechanism where visco-plastic flows of polymers are triggered. This is
 547 confirmed by the fact that five 1-week cycles are required for the stress state to reach the magnitude
 548 recorded during the first “saturation” cycle. This shows that the evolution of internal stresses depends not
 549 only on the magnitude of moisture content reached but also on the time spent at high moisture contents.
 550 This could be due to the viscoelastic behaviour and, therefore, the stress relaxation of the matrix and the
 551 mechano-sorptive behaviour of the fibre [49]. In the framework of an outdoor application, 24-hour cycles
 552 may be more representative of the lifetime of a biocomposite part as humidity varies from sunrise to
 553 sunset. “Saturation” cycles are thus extremely damaging. Interestingly, the flax/PP+MAPP biocomposites
 554 examined in this study are quite resistant to dry cycles and to wet cycles with low cycling periods.
 555 Nevertheless, the decrease in mechanical properties is linked to the relaxation of the internal stresses,
 556 which might be interesting in certain applications, such as when deformation induced by internal stresses
 557 is a drawback.
 558 Based on the results shown in the paper, Fig. 16 proposes a global scenario representing the stress state
 559 evolution within the biocomposites examined.



561 **Fig. 16 – Development of the stress state within the flax/PP+MAPP biocomposite. Step 1 is the solidification**
 562 **of the matrix. Step 2 is the demoulding of the part, Steps 3 to 5 are several steps of the moisture sorption of the**
 563 **biocomposite part.**

564 4. **Conclusion**

565 Natural fibre-reinforced biocomposite materials are sensitive to moisture variation and contribute to the
566 development of hygroscopic internal stresses. They have also been shown to be sensitive to the
567 hygroscopic cycling that is found in a wide range of outdoor applications. However, scant attention has
568 been paid in the literature to the evolution of internal stresses during cycles and their contribution to the
569 degradation of their overall properties.

570 The purpose of this article was to provide deeper insights regarding the development and evolution of
571 hygroscopic stresses within flax/PP+MAPP biocomposites during different hygroscopic cycles. Cycling
572 conditions such as cycling time from transient to saturation state and cycling RH boundaries were
573 evaluated. "Saturation" cycles, where the stabilization in mass triggered the change in condition, were
574 achieved at 23°C, between 11 and 50% RH, 50 and 99% RH, and between 11 and 99% RH. "Transient"
575 cycles with fixed periods were also used: 1-week cycles from 50 to 99% RH, and 24-hour cycles from 50
576 to 90% RH. The moisture content and curvature of asymmetric stripes and the deformations and stiffness
577 of unidirectional longitudinal and transversal tensile samples were examined throughout various
578 hygroscopic cycles.

579 Several phenomena, enhanced with the time spent at high moisture contents, were observed, leading to
580 the proposal of a degradation scenario:

- 581 - Loss in dry mass along the cycles, possibly due to the activation of the activity of
582 microorganisms;
- 583 - Permanent deformations in the out-of-plane direction, and thus increase in void content;
- 584 - Loss in longitudinal and transversal stiffness;
- 585 - Internal hygroscopic stresses higher than transverse strength of the biocomposites, which
586 induced damages at the fibre/matrix interface;
- 587 - Reduction of these internal stresses along cycles due to damage development and time-
588 dependent relaxation mechanisms (viscous flowing of the matrix, mechanosorptive behaviour of
589 fibre).

590

591

592

593 **Credit authorship contribution statement**

594 V Popineau: Investigation and writing; M Peron: review & editing; A Celino: supervision review &
595 editing; C Baley: Supervision, writing - review & editing; A Le Duigou: Supervision, fund acquisition,
596 writing - review & editing.

597

598 **Declaration of competing interest**

599 The authors declare that they have no known competing financial interests or personal relationships.

600

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604

605 **References**

- 606 [1] Gager V, Le Duigou A, Bourmaud A, Pierre F, Behlouli K, Baley C. Understanding the effect of
607 moisture variation on the hygromechanical properties of porosity-controlled nonwoven
608 biocomposites. *Polymer Testing* 2019;78 :105944.
609 <https://doi.org/10.1016/j.polymertesting.2019.105944>.
- 610 [2] Popineau V, Céline A, Le Gall M, Martineau L, Baley C, Le Duigou A. Vacuum-Bag-Only
611 (VBO) Molding of Flax Fiber-reinforced Thermoplastic Composites for Naval Shipyards.
612 *Applied Composite Materials* 2021. <https://doi.org/10.1007/s10443-021-09890-2>.
- 613 [3] Wambua P, Ivens J, Verpoest I. Natural fibres: can they replace glass in fibre reinforced plastics ?
614 *Composites Science and Technology* 2003;63:1259–64. [https://doi.org/10.1016/S0266-](https://doi.org/10.1016/S0266-3538(03)00096-4)
615 [3538\(03\)00096-4](https://doi.org/10.1016/S0266-3538(03)00096-4).
- 616 [4] Le Duigou A, Davies P, Baley C. Environmental impact analysis of the production of flax fibres
617 to be used as composite material reinforcement. *Journal of Biobased Materials and Bioenergy*
618 2011;5:1–13. <https://doi.org/10.1166/jbmb.2011.1116>.
- 619 [5] Hill C, Hughes M. Natural fibre reinforced composites opportunities and challenges. *Journal of*
620 *Biobased Materials and Bioenergy* 2010 ;4:148–58. <https://doi.org/10.1166/jbmb.2010.1079>.

- 621 [6] Le Duigou A, Merotte J, Bourmaud A, Davies P, Belhouli K, Baley C. Hygroscopic expansion: A
622 key point to describe natural fibre/polymer matrix interface bond strength. *Composites Science
623 and Technology* 2017;151:228–33. <https://doi.org/10.1016/j.compscitech.2017.08.028>.
- 624 [7] Péron M, Céline A, Dine, Castro M, Jacquemin F, Duigou A Le. Study of hygroscopic stresses in
625 asymmetric biocomposite laminates. *Composites Science and Technology* 2019 ;169:7–15.
626 <https://doi.org/S0266353818321602>.
- 627 [8] Parlevliet PP, Bersee HEN, Beukers A. Residual stresses in thermoplastic composites - a study of
628 the literature. Part I: Formation of residual stresses. *Composites Part A: Applied Science and
629 Manufacturing* 2007; 37, 11pp 1847-1857. <https://doi.org/10.1016/j.compositesa.2006.12.005>.
- 630 [9] Parlevliet PP, Bersee HEN, Beukers A. Residual stresses in thermoplastic composites - a study of
631 the literature. Part II: Experimental Techniques. *Composites Part A: Applied Science and
632 Manufacturing* 2007; 38, 3 pp 651-655. <https://doi.org/10.1016/j.compositesa.2006.12.005>.
- 633 [10] Parlevliet PP, Bersee HEN, Beukers A. Residual stresses in thermoplastic composites - a study of
634 the literature. Part III: Effects of thermal residual stresses. *Composites Part A: Applied Science
635 and Manufacturing* 2007; 6pp 1581-1596. <https://doi.org/10.1016/j.compositesa.2006.12.005>.
- 636 [11] Péron M, Jacquemin F, Casari P, Orange G, Bikard J, Bailleul J, et al. Measurement and
637 prediction of residual strains and stresses during the cooling of a glass fibre reinforced PA66
638 matrix composite. *Composites Part A: Applied Science and Manufacturing* 2020.
639 <https://doi.org/10.1016/j.compositesa.2020.106039>.
- 640 [12] Péron M, Céline A, Jacquemin F, Le Duigou A. Hygroscopic stresses in asymmetric
641 biocomposite laminates submitted to various relative humidity conditions. *Composites Part A:
642 Applied Science and Manufacturing* 2020; 134, 2020, 105896
643 <https://doi.org/10.1016/j.compositesa.2020.105896>.
- 644 [13] Timoshenko S. Analysis of bi-metal thermostats, *J. Opt. Soc. Am*,11,1925:233–55.
- 645 [14] Tacq J. Residual and internal stress development resulting from plastic deformation of multi-
646 phase alloys, doctoral thesis KU leuven (Belgium), 2015
- 647 [15] Lacoste E. Modélisation et simulation multi-échelles des contraintes d'élaboration et de service
648 dans les matériaux composites, doctoral thesis, University of Nantes (France), 2010.

- 649 [16] Thomason JL, Yang L, Gentles F. Characterisation of the anisotropic thermoelastic properties of
650 natural fibres for composite reinforcement. *Fibers* 2017; 5(4), 36.
651 <https://doi.org/10.3390/fib5040036>.
- 652 [17] Le Duigou A, Réquillé S, Beaugrand J, Scarpa F, Castro M. Natural fibres actuators for smart bio-
653 inspired hygromorph biocomposites. *Smart Materials and Structures* 2017;26.
654 <https://doi.org/10.1088/1361-665X/aa9410>.
- 655 [18] Céline A, Fréour S, Jacquemin F, Casari P. The hygroscopic behavior of plant fibers: a review.
656 *Frontiers in Chemistry* 2014;1. <https://doi.org/10.3389/fchem.2013.00043>.
- 657 [19] Sar BE, Fréour S, Davies P, Jacquemin F. Coupling moisture diffusion and internal mechanical
658 states in polymers - A thermodynamical approach. *European Journal of Mechanics, A/Solids*
659 2012;36:38–43. <https://doi.org/10.1016/j.euromechsol.2012.02.009>.
- 660 [20] BP Chan, AK. Mohanty and M Misra, Studies on durability of sustainable biobased composites: a
661 review, *RSC Adv.*, 2020, 10, 17955-17999
- 662 [21] Noor Azwa, B. F. Yousif, A Manalo, WM Karunasena, A review on the degradability of
663 polymeric composites base on natural fibres, 2013 *Mater and Des* 47:424-442
- 664 [22] Bailey, J.E., Curtis, P.T., Parvizi, A.: Transverse cracking and longitudinal splitting behavior of
665 glass and carbon-fiber reinforced epoxy cross ply laminates and the effect of poisson and
666 thermally generated strain. *Proc. R. Soc. Lond. Ser. A* 366(1727), 599–623 (1979)
- 667 [23] Penn LS, Chou RCT, Wang ASD, Binienda WK. The Effect of Matrix Shrinkage on Damage
668 Accumulation in Composites. *Journal of Composite Materials* 1988:570–86.
- 669 [24] Le Duigou A, Castro M. Moisture-induced self-shaping flax-reinforced polypropylene
670 biocomposite actuator. *Industrial Crops and Products* 2015;71:1–6.
671 <https://doi.org/10.1016/j.indcrop.2015.03.077>.
- 672 [25] Le Duigou A, Castro M. Evaluation of force generation mechanisms in natural, passive hydraulic
673 actuators. *Nature Publishing Group* 2016. <https://doi.org/10.1038/srep18105>.
- 674 [26] Le Duigou A, Castro M, Bevan R, Martin N. 3D printing of wood fibre biocomposites: From
675 mechanical to actuation functionality. *Materials and Design* 2016;96:106–14.
676 <https://doi.org/10.1016/j.matdes.2016.02.018>.

- 677 [27] Le Duigou A, Castro M. Hygromorph BioComposites: Effect of fibre content and interfacial
678 strength on the actuation performances. *Industrial Crops and Products* 2017;99:142–9.
679 <https://doi.org/10.1016/j.indcrop.2017.02.004>.
- 680 [28] Le Duigou A, Chabaud G, Scarpa F, Castro M. Bioinspired Electro-Thermo-Hygro Reversible
681 Shape-Changing Materials by 4D Printing. *Advanced Functional Materials* 2019;1903280:1–10.
682 <https://doi.org/10.1002/adfm.201903280>.
- 683 [29] Le Duigou A, Keryvin V, Beaugrand J, Pernes M, Scarpa F, Castro M. Humidity responsive
684 actuation of bioinspired hygromorph biocomposites (HBC) for adaptive structures. *Composites*
685 *Part A: Applied Science and Manufacturing* 2019;116:36–45.
686 <https://doi.org/10.1016/j.compositesa.2018.10.018>.
- 687 [30] Gassan J, Bledzki AK. Effect of Cyclic Moisture Absorption Desorption on the Mechanical
688 Properties of Silanized Jute-Epoxy Composites, *Polymer Composites*, 20, 4, 1999
- 689 [31] Kim HJ, Seo DW. Effect of water absorption fatigue on mechanical properties of sisal textile-
690 reinforced composites. *International Journal of Fatigue* 2006;28:1307–14.
691 <https://doi.org/10.1016/j.ijfatigue.2006.02.018>.
- 692 [32] Newman RH, Thumm A, Clauss EC, Guen MJ Le. Improving Hygrothermal Performance in
693 Epoxy-Biofibre Composites Improving Hygrothermal Performance in Epoxy-Biofibre
694 Composites, *Advanced Materials Research*. 29-30 (2007) pp 287-2902007.
695 <https://doi.org/10.4028/www.scientific.net/AMR.29-30.287>.
- 696 [33] Newman RH. Auto-accelerative water damage in an epoxy composite reinforced with plain-
697 weave flax fabric. *Composites Part A* 2009;40:1615–20.
698 <https://doi.org/10.1016/j.compositesa.2009.07.010>.
- 699 [34] Mak K, Fam A. The Effect of Wet-Dry Cycles on Tensile Properties of Unidirectional Flax Fiber
700 Reinforced Polymers. *Composites Part B : Engineering*, 183, 2020:107645.
701 <https://doi.org/10.1016/j.compositesb.2019.107645>.
- 702 [35] Cadu T, Van Schoors L, Sicot O, Moscardelli S, Divet L. Hygrothermal ageing of flax fibers'
703 bundles and unidirectional flax/ epoxy composite. Are bio-based reinforced composites so
704 sensitive ? *Industrial Crops & Products* 2019;141:111730.
705 <https://doi.org/10.1016/j.indcrop.2019.111730>.

- 706 [36] Van Schoors L, Cadu T, Moscardelli S, Divet L. Why cyclic hygrothermal ageing modifies the
707 transverse mechanical properties of a unidirectional epoxy-flax fibres composite ? *Industrial*
708 *Crop and Products*, 164, 2021, 113341, <https://doi.org/10.1016/j.indcrop.2021.113341>.
- 709 [37] Lu MM, Van Vuure AW. Improving moisture durability of fl ax fibre composites by using non-
710 dry fibres. *Composites Part A* 2019;123:301–9.
711 <https://doi.org/10.1016/j.compositesa.2019.05.029>.
- 712 [38] Khalfallah M, Abbès B, Abbès F, Guo YQ, Marcel V, Duval A, et al. Innovative flax tapes
713 reinforced Acrodur biocomposites : A new alternative for automotive applications. *Journal of*
714 *Materials & Design* 2014;64:116–26. <https://doi.org/10.1016/j.matdes.2014.07.029>.
- 715 [39] Baley C, Le Duigou A, Bourmaud A, Davies P. Influence of drying on the mechanical behaviour
716 of flax fibres and their unidirectional composites. *Composites Part A: Applied Science and*
717 *Manufacturing* 2012; 43:1226–33. <https://doi.org/10.1016/j.compositesa.2012.03.005>.
- 718 [40] Shah DU. Damage in biocomposites : Stiffness evolution of aligned plant fibre composites during
719 monotonic and cyclic fatigue loading. *Composites Part A: Applied Science and Manufacturing*
720 2016;83:160–8. <https://doi.org/10.1016/j.compositesa.2015.09.008>.
- 721 [41] Testoni G.A. In situ long-term durability analysis of biocomposites in the marine environment,
722 doctoral thesis, Ecole Nationale Supérieure des Mines de Paris, 2015. [https://pastel.archives-](https://pastel.archives-ouvertes.fr/tel-01299806)
723 [ouvertes.fr/tel-01299806](https://pastel.archives-ouvertes.fr/tel-01299806)
- 724 [42] Le Duigou A, Bourmaud A, Baley C. In-situ evaluation of flax fibre degradation during water
725 ageing. *Industrial Crops and Products* 2015;70:190–200.
726 <https://doi.org/10.1016/j.indcrop.2015.03.049>.
- 727 [43] Fernandes Diniz JMB, Gil MH, Castro JAAM. Hornification — its origin and interpretation in
728 wood pulps. *Wood Science and Technology* 2004;37:489–94. [https://doi.org/10.1007/s00226-](https://doi.org/10.1007/s00226-003-0216-2)
729 [003-0216-2](https://doi.org/10.1007/s00226-003-0216-2).
- 730 [44] S Park, RA.Venditti, HJ ameel, JJ. Pawlak, Changes in pore size distribution during the drying of
731 cellulose fibers as measured by differential scanning calorimetry, Volume 66, Issue 1, 2006,
732 Pages 97-103
- 733 [45] Fernando D, Thygesen A, Meyer AS, Daniel G. Elucidating Field Retting Mechanisms of Hemp
734 Fibres for Biocomposites : Effects of Microbial Actions and Interactions on the Cellular Micro-

735 morphology and Ultrastructure of Hemp Stems and Bast Fibres, *BioRes.* 14(2), 4047-
736 4084. <https://doi.org/10.15376/biores.14.2.4047-4084>.

737 [46] Réquillé S, Le Duigou A, Bourmaud A, Baley C. Deeper insights into the moisture-induced
738 hygroscopic and mechanical properties of hemp reinforced biocomposites. *Composites Part A*
739 2019;123:278–85. <https://doi.org/10.1016/j.compositesa.2019.05.006>.

740 [47] Holstov A, Farmer G, Bridgens B. Sustainable Materialisation of Responsive Architecture.
741 *Sustainability*, 9, 435; 2017, <https://doi.org/10.3390/su9030435>.

742 [48] Chen M, Coasne B, Guyer R, Derome D, Carmeliet J. Role of hydrogen bonding in hysteresis
743 observed in sorption-induced swelling of soft nanoporous polymers. *Nature Communications*,
744 9,3507, 2018, <https://doi.org/10.1038/s41467-018-05897-9>.

745 [49] Cissé O, Placet V, Boubakar, L. Mechanosorptive creep in single hemp fibres. *Composites week*
746 @Leuven and Texcomp-11 Conference, Jan 2013, pp.1 - 7, 2013.<hal-00993418>

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752 5. **Appendix 1**

753 Linear regressions are calculated from the results presented in Fig. 7a and b, and Fig.13a and b, for the
754 evolutions of the longitudinal and transversal stiffness across the different hygroscopic cycles. The values
755 used in the calculations of the stress states for the longitudinal and transversal stiffnesses E_1 and E_T are
756 respectively calculated with the following equations:

$$757 \quad E_1 = E_{1,0} + a_L * CY \quad \text{Eq. 5}$$

$$758 \quad E_T = E_{T,0} + a_T * CY \quad \text{Eq. 6}$$

759 with CY the number of the cycle at which the stiffnesses are calculated, and $E_{1,0}$, $E_{T,0}$, a_L , and a_T , the
760 parameters of the linear regressions. Those parameters depend on the hygroscopic cycle methodology and
761 are presented in Table 1.

762 Table 1 - Parameters of the linear regressions for the evolution of longitudinal and transversal stiffnesses
763 across the different hygroscopic cycles

	Longitudinal Stiffness E_1		Transversal Stiffness E_T	
	$E_{1,0}$ (GPa)	a_L (MPa/Cy)	$E_{T,0}$ (GPa)	a_T (MPa/Cy)
Saturation cycles: 11 - 50% RH	23.8	-188	1.73	-55.8
Saturation cycles: 50 - 99% RH	22.6	-824	1.45	-86.7
Saturation cycles: 11 - 99% RH	23.1	-1004	1.44	-121
24-hour cycles 50 - 90% RH	23.3	-27.9	1.49	-3.35
1-week cycles 50 - 99% RH	23.8	-164	1.57	-27.3

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