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Evaluation of Woven Hemp-Reinforced Polyfurfuryl Alcohol Resin Composites for High-Performance Natural Fibre Composite Applications

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Abstract

The escalating environmental concerns associated with the non-renewable nature of petrochemical-based composite constituents have accelerated the development of sustainable and renewable alternatives. This study evaluates the potential of woven hemp-reinforced polyfurfuryl alcohol (PFA, furan) composites as fully bio-based composite materials. The use of PFA, a fully bio-based resin renowned for its high rigidity and fire-retardant properties, has been hindered by challenges associated with water vapour evolution, acid-catalysed fibre degradation, and porosity formation. Novel woven long hemp fibres were combined with a polyfurfuryl alcohol resin formulated with a mild acid catalyst, while an early-stage venting procedure during compression moulding was investigated to mitigate porosity and fibre degradation. Thermogravimetric analysis was used to determine the venting moments during the moulding cycle. Despite the limited improvement in porosity reduction achieved through the investigated venting strategy, the hemp balanced satin 6/6 fabric–furan composites exhibited commendable stiffness with a maximum modulus of 17.0 $\pm$ 0.4 GPa. However, the inherent brittleness of the resin and possibly the presence of fire-retardant fillers limited the tensile strength (a maximum of 71.8 $\pm$ 4.2 MPa) and failure strain (a maximum of 0.72 $\pm$ 0.07%). The bending properties of neat furan resin produced using an improved curing protocol were comparable to those of conventional thermoset resins, with a modulus of 3.2 $\pm$ 0.2 GPa, strength of 110.5 $\pm$ 17.3 MPa, and failure strain of 4.1 $\pm$ 0.8%. Although several challenges remain, this study demonstrates the potential of natural fibre–furan composites for high-performance natural fibre composite applications and provides guidance for their further development. Future research should focus on optimising venting strategies, avoiding fire retardants to minimise resin brittleness, incorporating matrix tougheners, and enhancing the inherent toughness of the matrix.

Keywords: polyfurfuryl alcohol; hemp fibre; natural fibre composites; mechanical properties; porosity reduction; manufacturing optimisation

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1. Introduction

The non-renewable nature of petrochemical-based constituents and rising environmental concerns have caused rapid growth in the development of sustainable and renewable alternatives to conventional constituents of polymeric composites [1,2]. Considerable attention has been given to using plant-based fibres like flax, hemp, jute, and bamboo as reinforcements [3,4]. Recently, along with using natural fibres as reinforcements, there has been a notable focus towards exploring the potential of bio-based matrices to fulfil the desire for fully crop-derived composites [5–7]. Adopting bio-based matrices and reinforcements not only facilitates the reduction of carbon footprint and greenhouse gas emissions but also promotes a circular economy by utilising agricultural waste and bio-resources that would otherwise go to waste.

The concept of using bio-based matrices revolves around incorporating organic and sustainable materials derived from biomass, such as plant-based polymers or bio-resins, into the composite manufacturing process. An example is polyfurfuryl alcohol resin (PFA), also known as furan resin, produced from hemi-cellulose-rich biomass such as rice hulls or sugarcane bagasse. The process involves acid-catalysed hydrolysis of biomass to obtain bio sugar followed by acid-catalysed dehydration to produce furfural [8,9]. Hydrogenation of furfural yields furfuryl alcohol, which undergoes acid-catalysed polymerisation at elevated temperatures to form polyfurfuryl alcohol, a renewable thermoset resin with excellent rigidity and fire-retardant properties [10–12].

Given the limited availability of bio-based thermoset resins in the current market and the growing demand for fully bio-based composites, this raises a question as to why the utilisation of PFA has not yet gained significant traction within the realm of natural fibre composites. The literature mainly highlights the following challenges associated with using PFA as a matrix in natural fibre composites: (i) occurrence of porosities due to evaporation of residual water and water generated during polycondensation, (ii) degradation of fibres catalysed by acidic conditions stemming from low pH levels, and (iii) low failure strain as a consequence of the inherent brittle characteristics of the resin [13–16].

Most commercially available furan resins incorporate water as a solvent to reduce viscosity and enhance processability. Moreover, due to the polycondensation reaction during curing, water is released. Consequently, the processing of these resins at elevated temperatures leads to the formation of water vapour, creating microvoids which adversely affect the mechanical properties [13,17]. Matrix porosity can be decreased by a slow stepwise increase in processing temperatures to allow the moisture to evaporate before the resin starts to gel. However, very slow processing would not be an industrially viable solution. In the case of natural fibre composites, lignocellulosic fibres are prone to acid-catalysed degradation. Thygesen et al. [18] demonstrated that the strength of hemp fibres remains relatively stable within the pH range of 7 to 4, but experiences significant deterioration when the pH decreases below 3. In addition, the fibre-matrix interface may degrade due to fibre shrinkage, which is detrimental to the mechanical properties of composites. Consequently, industrial producers of furan resin, for example, TransFuran Chemicals, Belgium, have developed grades with mild acid catalysts suitable for natural fibres with a pH range of 4–5 [15].

Furthermore, furan resin is inherently brittle due to its high aromatic content and crosslinking density. However, our earlier study showed that the brittleness of furan can be reduced by copolymerisation with varying comonomer amounts, inhibiting the conjugation and crosslinking reactions [16]. The mechanical properties of glass fibre-reinforced furan composites are typically closer to the theoretical value as determined based on the constituent properties compared to those of natural-fibre furan composites [19,20]. The smaller deviation in mechanical properties from the theoretical values for glass fibre

furan composites indicates that using furan resin may not inherently pose issues; however, challenges may arise when it is combined with natural fibres. The potential causes of deviated mechanical properties of natural fibre composites are moisture-induced or acid-catalysed fibre degradation and dimensional changes, such as fibre swelling or shrinking during the processing. However, using natural fibre could be advantageous in reducing the porosity due to water vapour. Fauster et al. [21] evidenced a reduction in porosity content of furan composites due to the hydrophilic nature of natural fibre, since water present in the resin or released during cure may be absorbed by the fibres.

Here, we evaluate the potential of woven hemp-reinforced polyfurfuryl alcohol composites for high-performance natural fibre composite applications by addressing the key processing challenges associated with this material system. Specifically, this study investigates (i) the use of novel woven long hemp fibres, (ii) the optimisation of the compression moulding process through an early-stage venting strategy to reduce porosity, and (iii) the use of a mild acid catalyst to limit fibre degradation. In addition, the mechanical behaviour of the neat resin is evaluated to better understand the factors governing the performance of the resulting composites. Novel woven reinforcements consisting of long hemp fibres are combined with polyfurfuryl alcohol, a mild acid catalyst, and an ammonium polyphosphate (APP) fire retardant in a prepreg process. Firstly, a standard compression moulding process is used to produce the composites, and static mechanical properties are determined. Secondly, to limit composite porosity, alternative composite manufacturing protocols are evaluated in which steam is released before the gelation of the resin, followed by curing at high pressure to disperse the remaining water into small droplets. Thirdly, the mechanical properties of the neat resin cured using standard and alternative protocols are determined since the resin should have adequate stiffness, strength, and failure strain for use in high-performance composite applications.

2. Materials and Methods

2.1. Materials

Four layers of woven hemp fabric pre-impregnated with PFA resin were used to produce composites. The production of woven hemp fabrics was a collaborative effort within the H2020 SSUCHY project consortium [22]. Hemp stems were converted into long-fibre hemp by Terre De Lin, France, adopting scutching and hackling lines traditionally used for flax. Linificio e Canapificio Nazionale Srl (LCN), Villa d'Almè, Italy, converted the resulting hemp sliver into low-twist rovings and a satin 6 preform. Both balanced and unbalanced hemp satin 6 weaves were produced, having a pick-over count ratio (cm^{-1}/cm^{-1}) of 6.5/6.5 and 6.5/9.5, respectively.

Subsequently, B-staged hemp weave–PFA prepregs were produced by Basaltex NV, Wevelgem, Belgium. The resin mixture consisted of PFA resin tradename Furolite 120621 of TFC Belgium (Geel, Belgium), a mild acid catalyst (2-hydroxyethyl ammonium nitrate, ALTON HM 1448, WIZ chemicals, Dairago, Italy) to minimise acid degradation of the fibres, an ammonium polyphosphate (APP) fire retardant to further improve the intrinsic fire-retardant properties of the resin, and a small amount of water to adjust the viscosity. The respective mixing ratios were 6 wt% based on the weight of the resin and 15 wt% based on the total resin mixture without water. After the prepreg process, solvent water was evaporated in an oven at 100 °C for 4 min. The resulting B-staged (partially cured) balanced and unbalanced satin 6 weaves had a resin pick-up ratio of 52 and 44% wt%, respectively.

Resin samples were produced with the same PFA grade, Furolite 120621, and a mild acid catalyst as mentioned above. No additives were used in the neat resin samples.

2.2. Processing

Composite laminates of 250 × 250 × 3 mm were produced using compression moulding. To study the influence of steam release, the hot press was opened at various moments in the curing cycle. Apart from the mould opening frequency, all other processing parameters remained constant. The processing temperature and pressure were set at 155 °C and 15 bar, respectively. The total processing time and moments of mould opening were selected based on the results of the thermogravimetric analysis and oven-curing experiment described in Section 2.3. An overview of the processing parameters is shown in Table 1. The warp direction of all layers of prepreg was aligned.

Table 1. Overview of processing parameters.

Fabric Type	Temperature (°C)	Pressure (Bar)	Total Processing Time (min)	Mould Opening at (min)
Unbalanced satin 6	155	15	20	/
	155	15	20	1.5
	155	15	20	3
	155	15	20	5
Balanced satin 6	155	15	20	/
	155	15	20	1.5 and 3
	155	15	20	1.5, 3 and 5

Dumbbell-shaped resin samples were cast in a silicone mould and oven-cured via two protocols. The aim was to produce porosity-free samples to determine the maximum reinforcement potential of the resin. Protocol 1 followed the same method as described by Sharib et al. [23], where the samples were cured at 50 °C for 96 h, 100 °C for 1 h, and 150 °C for 30 min. In protocol 2, the mixture was first degassed and partially cured in a vacuum oven at 50 °C for 30 min before it was cast. Thereafter, the same curing protocol was followed.

2.3. Thermogravimetric Analysis (TGA)

Thermogravimetric analysis (TGA) was performed on a CAHN TG 171-09s (TA Instruments, New Castle, DE, USA) to evaluate the curing behaviour. The weight reduction of the sample can be correlated with the degree of cure since water is released during the polycondensation reaction. A small piece of prepreg (ca.10 mg) was heated up to 155 °C with a heating rate of 30 °C/min and held at this temperature for 20 min.

Like TGA analysis, the weight decrease of prepreg samples was also recorded when cured in an oven at 155 °C, which allowed the use of larger samples (ca.50 × 50 mm). The measurement interval was varied between 2, 4, and 8 min to limit the temperature variation in the oven.

2.4. Mechanical Properties

The mechanical properties were determined on a ZwickRoell Z100 universal testing machine (ZwickRoell, Ulm, Germany) equipped with a 100 kN load cell and clip-on extensometer. The ASTM 3039 standard [24] was followed. A displacement rate of 2 mm/min was used. The mechanical tests were performed under general laboratory conditions at room temperature.

2.5. Computed Tomography

The porosity and additive volume characterisation of composites were performed by a high-resolution computed nano-tomography system (nano-CT) (RX Solution EasyTom 160, Chavanod, France), equipped with an X-ray source Hamamatsu Open Type Microfocus

L10711 (Hamamatsu, Japan) and a flat panel detector 2530DX (Varex Imaging, Salt Lake City, UT, USA) of 2176 × 1792 pixels^2. The accelerating voltage and the electric current were fixed at 60 kV and 86 µA, respectively. The exposure time was set at 1 image/s with an average frame of 3 images. A total of 1440 projections were collected for each sample, resulting in a time of 2 h per tomograph. The entire volume of samples (3–5 mm^3) was reconstructed at full resolution with a voxel size of 1.2 µm corresponding to a field of view of 2.4 × 2.2 mm^2, using a filtered back-projection algorithm.

The data analysis to determine porosity and additive content was performed using VG StudioMax 3.5 software. A segmentation was realised using porosity and additives functions implemented in VG StudioMax software, as well as interpreted thresholds and prior knowledge. Three distinct peaks were found in the multimodal image histogram. These peaks were attributed to air, material, and additive. Greyscale-based thresholds were then positioned between the respective peaks, and each material family was then represented by a colour: material in grey, porosity in blue, and additive in green. The porosity and additive measurements were performed on the volume excluding the edge regions to avoid edge effects. The volume of porosity (V_p) is calculated with Equation (1), where V_c is the volume of the cube and V_m is the volume of the material (method 1). The same calculation was done for the volume of the additive. The values of porosity and additive are reported in Table 2.

$$V_p = V_c - V_m \quad (1)$$

2.6. Calculations

An overview of the equations and adopted parameters used to derive the fibre volume fraction based on the weighing method and the back-calculated yarn stiffness is described next. The fibre volume fraction, V_f, is calculated according to Equation (2) (method 2). The areal weight of the balanced and unbalanced satin 6/6 fabrics were 340 g/m^2 and 425 g/m^2, respectively. A hemp fibre density of 1.5 g/cm^3 was used [25].

$$V_f = {}^{m_{fibres}}/_{\rho_{fibres}}/_{V_{composite}} \quad (2)$$

The back-calculated yarn stiffness, $E_{f\parallel}$, is determined based on the simple rule of mixtures (Equation (3)). The composite and matrix stiffness, E_c and E_m, are experimentally determined, while yarn stiffness was obtained through the European Union's SSUCHY project (https://www.ssuchy.eu (accessed on 8 June 2026)). The transverse yarn stiffness, $E_{f\perp}$, and the matrix stiffness, E_m, were set at 6 and 3 GPa, respectively.

$$E_c = E_{f\parallel} * V_{f\parallel} + E_{f\perp} * V_{f\perp} + E_m * \left(1 - V_f\right) \quad (3)$$

3. Results

3.1. Pre-Manufacturing Determination of Curing Rate

The curing rate of the B-staged prepregs was first evaluated to determine a suitable manufacturing protocol for composites from laminates. The evaluation was based on thermogravimetric analysis (TGA) and the recorded weight change during oven curing of a 50 × 50 mm prepreg layer. The polycondensation reaction of furan resin leads to the release of water, which allows the curing characteristics to be evaluated based on weight measurements.

Important to note is that the weight reduction might not solely be linked with PFA curing. Evaporation of remaining moisture in the fibres and resin can also contribute to the weight reduction. In addition, the pressure, heating rate, and dimensions of the samples differ from the actual processing conditions. However, determining the curing rate based on

weight variations during the actual production process was proven to be difficult as small amounts of resin leakage were unavoidable [21]. Therefore, the oven-curing experiment and thermogravimetric analysis give an approximation of the actual curing rate in the hot press-based manufacturing process. Another way of determining the curing rate during processing might be to use a fully closed mould or to lower the pressures; however, low pressure during manufacturing will have other disadvantages, such as the creation of voids and air bubbles.

The TGA results of a small piece of prepreg, approximately 15 mg, when heated to 155 °C and held at this value for 20 min, show a weight stabilisation after approximately 5 min (Figure 1a). The weight stabilisation at ca. 5 min indicates that the resin was adequately cured, and the remaining volatile substances were evaporated. An earlier study, where the curing kinetics of the furan resin and its composites were characterised by Differential Scanning Calorimetry, showed that the highest achievable crosslink density was reached after 5 min when cured at 155 °C [26]. Next, the weight reduction of a 50 × 50 mm prepreg layer during oven curing at 155 °C was measured (Figure 1b). The measurement interval is increased from 2 to 8 min to minimise the effect of temperature fluctuations resulting from opening the oven. Results show that the maximum weight decrease was 9–10%, which is in good correlation with the TGA results. Depending on the measurement interval, and thus the actual temperature in the oven, approximately 55–75% of the moisture is released during the first 5 min, while a constant weight is reached after approximately 10 min.

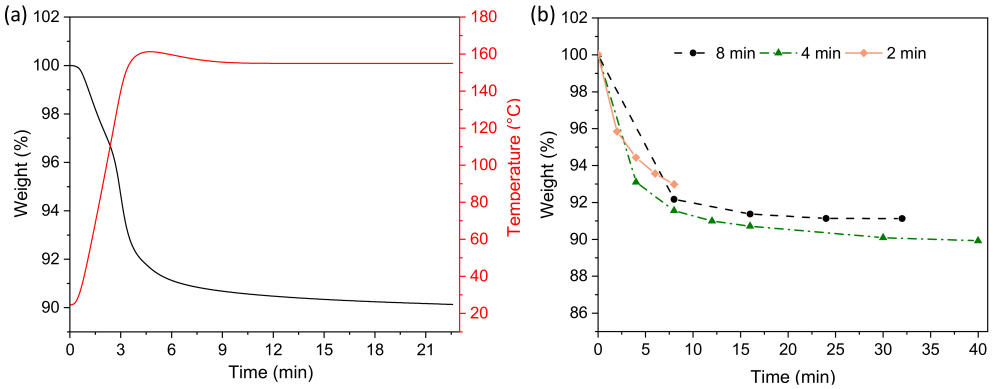

Figure 1. (**a**) TGA measurement of a small prepreg sample. The weight reduction over time is shown in black and projected on the primary *y*-axis. The temperature profile is shown in red and projected on the other *y*-axis. (**b**) Weight reduction of a 50 × 50 mm prepreg sample measured at different time intervals during oven curing at 155 °C.

Although it was difficult to simulate the actual processing conditions, the TGA and oven-curing experiments indicate that a high curing degree is reached, and most water is evaporated, within 5 min when the B-staged prepreg is processed at 155 °C. Furthermore, it is evident that a processing time of ca. 20 min is sufficient for effective furan curing, as indicated by the stabilisation of weight loss in both TGA and oven-curing analyses (Figure 1). Accordingly, the TGA and oven-curing experiments were primarily used to identify the curing kinetics and define the venting window. A processing time of 20 min was retained to ensure uniform heat transfer, complete laminate consolidation, and full curing throughout the thickness of the four-layer composite laminate under compression.

3.2. Mechanical Properties of Composites Manufactured with Different Protocols

The influence of the production process on the mechanical properties of hemp weave furan composites is evaluated. We investigated the release of steam during processing by

opening the mould, anticipating a reduction in composite porosity and consequently an enhancement in its mechanical properties.

To produce hemp unbalanced satin 6-reinforced furan composites, the mould was opened after 1.5, 3, and 5 min to evaluate the influence of steam release. The composite strength and stiffness both increase by 12% to 14 GPa and 58 MPa when steam is released after 1.5 min. This might indicate that the porosity content was reduced, which will be discussed in the following Section 3.3. However, when the mould was opened in a later stage of the curing cycle, after 3 or 5 min, the laminate showed strong delamination after production, meaning that the consolidation was poor. Although the sample dimensions and heating rate differ, the TGA and oven-curing experiments indicate that a high degree of cure is reached after ca. 3–5 min. As a result, the flow of the PFA resin between the layers might be hindered when the hot press was closed after steam release, leading to weaker interactions between the layers of prepreg. The latter indicates that the processing window of steam release is smaller than previously anticipated.

The influence of the frequency of steam release was evaluated during the production of the balanced satin 6 furan composites, as shown in Figure 2. Important to note is that opening the hot press influences the actual temperature in the laminate, meaning that the curing degree at a certain moment in time is influenced by the frequency of steam release. Results show a slight increase in composite strength when the mould is opened after 1.5 and 3 min. A combination of delamination and tensile failure was observed visually for the composites opened after 5 min. Similarly, as for the composites produced with the unbalanced fabrics, the shift in properties might be explained by a reduction in porosity content and poor compaction when the press was opened in a late stage of the curing cycle.

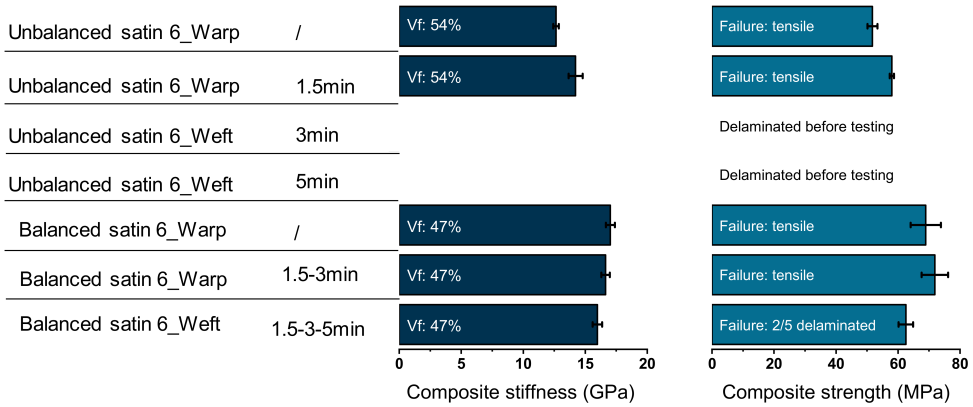

Figure 2. Mechanical properties of hemp weave furan composites obtained by tensile tests. The test direction, warp or weft, is mentioned in the name. The columns, starting from the left, show the weave type and the moments of steam release. Within the bars, the fibre volume fraction, Vf, and the failure behaviour, tensile or combined tensile/delamination, are shown. "2/5 delaminated" indicates that two of the five specimens showed a combined tensile/delamination failure, and the others failed in tension.

The back-calculated yarn stiffness, a method described in Section 2.6, and composite failure strain show a yarn stiffness of 40–55 GPa, matching the expectations (Figure 3) [27]. However, the composite failure strain was low, which might be linked with a high porosity content or with the inherent brittleness of the matrix. Variations in back-calculated yarn stiffness might be explained by the variation in yarn twist and crimp, and an over/underestimation of the fibre volume fraction. The fibre volume fraction determined based on the weight of the fabric, the density of hemp fibre, and the volume of the composite (method 2) and fibre volume fraction determined by μCT (method 1) showed differences

up to 5%, e.g., Vf (method 2) = 54% vs. Vf (method 1) = 49%. Method 2 was opted for as this is the standard in the literature.

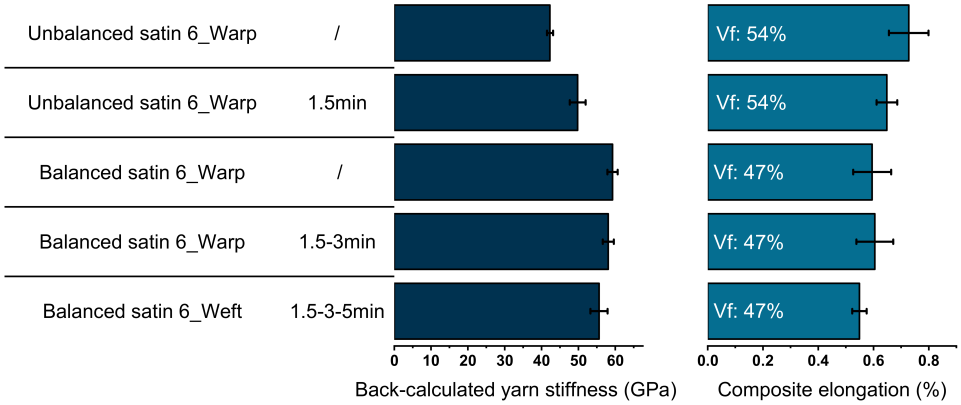

Figure 3. Back-calculated yarn properties adopting the simple rule of mixtures and the composite failure strain. The columns, starting from the left, show the weave type and the moments of steam release. The fibre volume fraction based on the weight of the fabric and the volume of the composite is shown in the bars.

To conclude, the stiffness of the hemp weave-reinforced PFA composites is in good agreement with the theory. However, the strength was limited to 50–70 MPa. Unfortunately, although venting in an early stage of the curing cycle led to an increase in stiffness and strength up to 12%, the suggested process yielded only marginal enhancements compared to the production protocols documented in the existing literature. High porosity content and the intrinsic brittleness of the resin might be an explanation for the low strength values.

3.3. Porosity Analysis by Computed Tomography

Nano-computed tomography results on porosity and additive content show that the porosity content of composites was 5–11%, which, at least partially, explains the low strength performance of the composites in general (Table 1). Extensive venting had a limiting influence on the porosity content, which is in line with the variation in mechanical properties. Nano-CT images of samples vented at different times show an increase in macroscopic porosity for both the unbalanced satin weave (Figure 4a,b) and the balanced satin weave (Figure 4c–e), even when venting was performed after only 1.5 min. The macroscopic porosities were mostly present at the crossing of warp and weft roving, as shown in Figure 4. Therefore, future research should investigate the effect of venting in the first stage of the curing process, before 1.5 min. Perhaps a venting protocol with a frequency of 20 s could lead to a reduction in porosity. Another way could be the development of a manufacturing process with continuous venting in the earlier stage of curing. The presence of fire-retardant additives was visualised with computed tomography, and the volume fraction corresponded to 5–6% (Figure 4f,g, Table 2). The presence of fire retardant did not seem to cause any porosity in the samples, but may cause embrittlement of the resin.

Table 2. Porosity and additive measurement in nano-CT.

Same Name	Porosity (%)	Additive (%)
Unbalanced satin 6_Warp	4.4	6.5
Unbalanced satin 6_Warp 1.5 min	5.1	5.1
Balanced satin 6_Warp	10	5.7
Balanced satin 6_Warp 1.5–3 min	11	6.3
Balanced satin 6_Warp 1.5–3–5 min	11	10

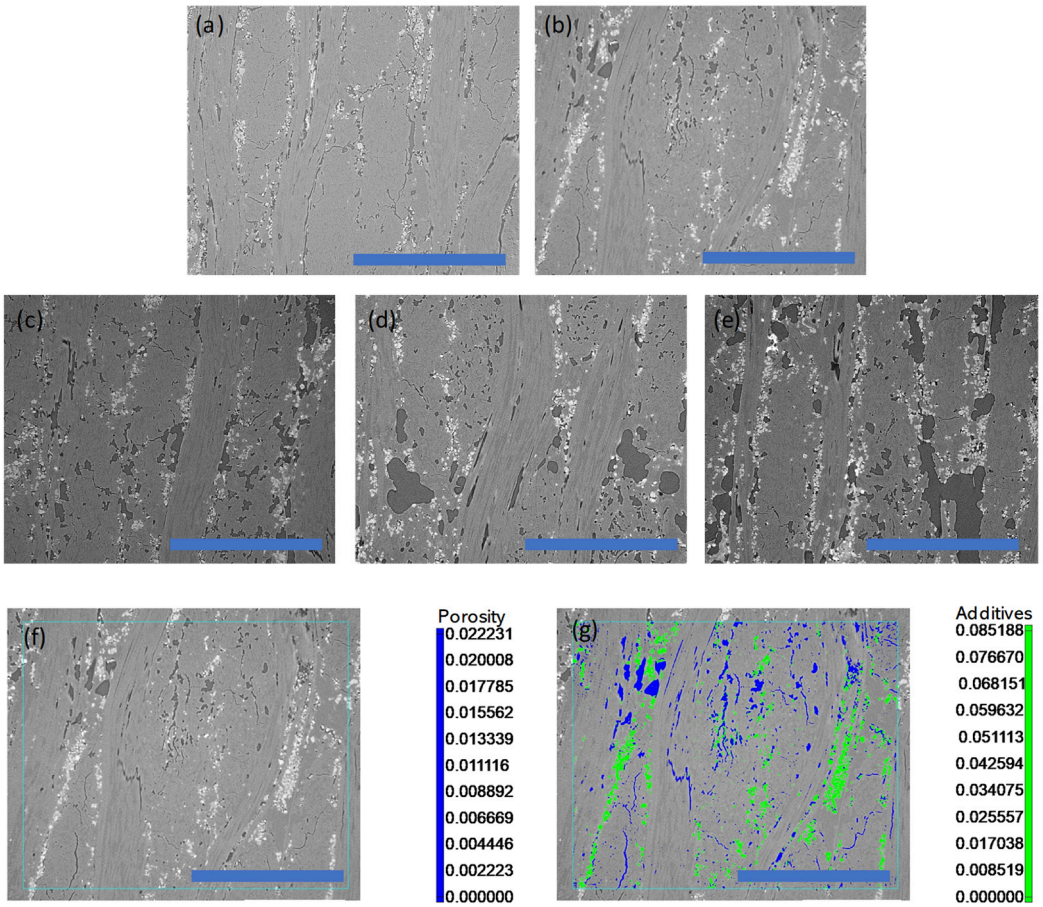

Figure 4. Nano-CT images of (**a**) unbalanced satin 6_warp, (**b**) unbalanced satin 6_warp 1.5 min s, (**c**) balanced satin_6 warp, (**d**) balanced satin_6 warp 1.5–3 min, and (**e**) balanced satin_6 warp 1.5–3–5 min. Internal 2D slice in a scanned volume of the unbalanced specimen, (**f**) slice without analysis and (**g**) slice after the analysis. The scale bar represents 0.75 mm. The blue box indicates the region of interest used for porosity and additive measurements to avoid edge effects.

3.4. Properties of Neat PFA Resin

Since brittleness was indicated as one of the factors for the poor strength and failure strain of hemp–furan composites, the properties of the neat resin were studied. Images of the samples and results of the tensile and bending tests are shown in Figure 5. Visual observation showed that the samples produced via protocol 1 (Figure 5a) contained porosities concentrated at the surface, and porosity-free samples were obtained via protocol 2 (Figure 5b, details of protocols in Section 2.2). A stiffness of 2.5–4 GPa was reported regardless of the presence of porosity or loading case, which is comparable with traditional thermoset resins for composite production like polyester and epoxy. However, results showed that the failure strain and strength were rather low, especially in tension (Figure 5c). Even in the best-case scenario (porosity-free composites), the failure strain of the matrix is lower than that of the fibres when subjected to tensile loading, meaning that failure will occur before the maximum strength of the fibres is reached. Hence, the inherent brittleness of the resin is an explanation for the low strength and failure strain of the hemp fibre-reinforced furan composites discussed in Section 3.2. Moreover, the brittle behaviour of the matrix may be further amplified by the presence of the fire retardant, since strain magnification can occur near these particulate additives. However, the individual contribution of APP was not investigated in the present study and should be addressed in future work. The results in bending were encouraging since a strength and failure strain of 110 MPa and 4% were reached, respectively, which indicates that high-performance

hemp–furan composites may be possible (Figure 5d). The higher tensile and bending strengths obtained using protocol 2 are attributed to the vacuum degassing step prior to curing, which effectively reduced porosity in the resin. The presence of pores acts as stress concentrators that promote premature crack initiation and propagation, thereby reducing the strength of brittle thermosetting polymers. This interpretation is consistent with previous studies reporting the detrimental influence of porosity on the mechanical performance of polyfurfuryl alcohol resins and composites [17,21].

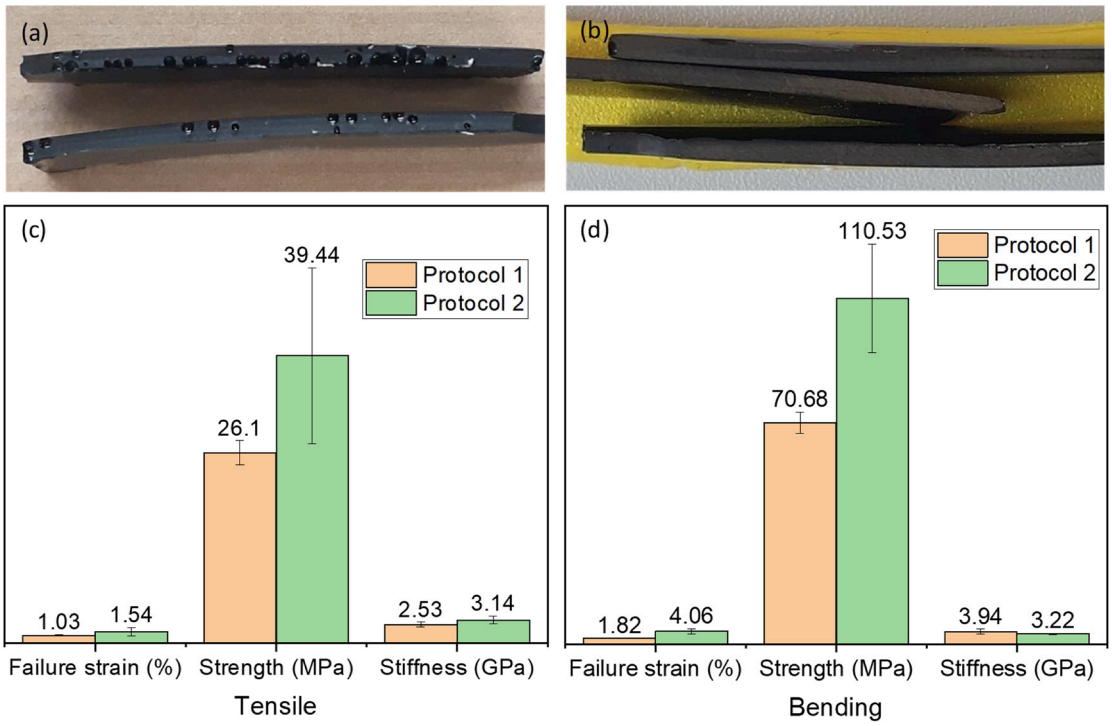

Figure 5. Representative neat furan samples produced using Protocol 1 (**a**) and Protocol 2 (**b**), as described in Section 2.2. The corresponding mechanical properties obtained from tensile (**c**) and bending (**d**) tests.

4. Discussion

There has been very limited research on natural fibre–furan composites (Table 3). Among them, most studies have investigated the potential of flax fibre-reinforced furan composites, with only a few focusing on hemp–furan composites. Pohl et al. [20] investigated the properties of compression-moulded furan composites with aligned flax fibre textiles. The maximum tensile modulus and strength obtained in their study were 13 GPa and 70 MPa, respectively, with aligned fibres 0°/90° layer directions. Crossley et al. [28] used vacuum and compression mould methods to produce furan composites with unidirectional (UD) flax and 2 × 2 twill flax. They observed the maximum tensile modulus and strength of 25.6 GPa and 211 MPa, respectively, with UD flax–furan composites produced by compression moulding, whereas the UD flax–furan composites produced with vacuum mould exhibited tensile modulus and strength of 10.2 GPa and 59.5 MPa, respectively. In another report, they used a longer processing time of 240 min with a vacuum mould to produce UD flax–furan composites to have the tensile modulus and strength of only 5.6 GPa and 41 MPa, respectively [19], indicating that the compression moulding process is advantageous. Resch-Fauster et al. [21] examined the influence of the water absorption capacity of reinforcing fibres on the processability, morphology, and performance of furan composites. They found furan composites produced with hemp fabric to have tensile modulus and strength of 9 GPa and 75 MPa, respectively, and concluded that due to con-

densation reaction during furan curing, it is essential to optimise processing parameters to prevent the formation of steam bubbles within the composite and to ensure the production of higher-quality composites. Our study aimed to address this issue by introducing an early-stage venting step during processing. Although the investigated venting strategy resulted in only limited reductions in porosity, it provides important insight into the narrow processing window and indicates that alternative venting approaches, such as earlier or continuous venting, should be explored. Nevertheless, the introduced protocol with elevated pressure and optimised processing time led to composites with an improved modulus of 17.0 ± 0.4 GPa and comparable strength of 68.9 ± 4.8 MPa using hemp balanced satin 6/6 fabric. In addition to natural fibre–furan composites, research has also been conducted on glass-fibre- and furan-reinforced composites, demonstrating the potential of furan as an alternative bio-based resin for high-performance natural fibre composite applications [15,19,29–31].

Table 3. Overview of studies conducted on natural fibre-reinforced furan composites.

	Manufacturing Process		**Mechanical Properties (Tensile)**			
Fibre	**Process Parameters**	**Vent Protocol**	**Modulus (GPa)**	**Strength (MPa)**	**Strain (%)**	**Reference**
Flax (biaxial NCF, non-woven)	Compression (150 °C, 20 Bar, 470 s)	Yes	8–13	46–70	0.6–0.7	[20]
Flax (UD, 2 × 2 Twill)	Vacuumbag (150 °C, −1 Bar, 20 min) Open mould (140 °C, 20 Bar, 20 min)	No	6–26	59–211	-	[28]
Flax (UD)	Vacuumbag (60 °C, −1 Bar, 240 min)	No	5.6 ± 0.2	41.0 ± 3.7	0.8 ± 0.1	[19]
Hemp (Plain weave, Nonwoven)	Compression (155 °C, 10 Bar, 5 min)	Yes	9	50–75		[21]
Hemp (Woven)	Compression (155 °C, 15 Bar, 20 min) Venting at 1.5, 3 and 5 min	Yes	13–17	52–71	0.6–0.7	This study

5. Conclusions

Polyfurfuryl alcohol or furan is a 100% bio-based resin with excellent rigidity and fire retardancy, which has high potential for application in natural fibre-reinforced composites. However, widespread application is hindered by acid degradation of the fibres due to the use of acid catalysts, the formation of porosities in the composites resulting from moisture evaporation during processing at elevated temperatures, and the inherent brittleness of the resin.

In this study, woven long-fibre hemp–furan prepregs were successfully produced and used for composite manufacturing via compression moulding. A mild acid catalyst was used to limit fibre degradation, and the compression moulding cycle was varied to limit the formation of porosity. Thermogravimetric analysis showed that the prepreg reached a high degree of cure within 5 min, which was used to determine the venting moments during the moulding cycle. However, the investigated venting strategy had only a limited effect on reducing porosity, with nano-computed tomography revealing a porosity content of 5–11%.

The hemp–furan composites exhibited a maximum tensile modulus of 17.0 ± 0.4 GPa, corresponding to the expected maximum hemp yarn stiffness contribution of approximately 55 GPa, while the tensile strength and failure strain were limited to approximately 70 MPa and 0.6%, respectively. These limitations are attributed to the relatively high porosity and the inherent brittleness of the PFA matrix, which may be further amplified by the presence

of the fire retardant. The neat PFA resin produced using the improved curing protocol exhibited promising bending properties comparable to conventional thermoset resins.

Although several challenges remain, the results demonstrate the potential of PFA-based natural fibre composites for high-performance natural fibre composite applications. The present study further identifies the limitations of the investigated venting strategy and provides guidance for future process optimisation. Future work should investigate venting before 1.5 min or continuous venting during the early stages of curing to further reduce porosity. In addition, avoiding fire retardants, enhancing the inherent toughness of the matrix, and incorporating matrix tougheners are expected to further improve the mechanical performance of hemp–furan composites.

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Data Availability Statement: The data generated in this study are available within the article. Additional data and raw datasets supporting the findings of this study are available from the corresponding author upon reasonable request.

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