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Title: Thermoformability characterisation of Flax reinforced polypropylene composite materials

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ABSTRACT

Flax reinforced polypropylene (Flax/PP) composites are currently used as sustainable and recyclable materials in secondary load-bearing applications. This study focuses on the effects of the thermoforming parameters (temperature, dwelling time, pressure and fabricated area parameters) and moisture absorption on the mechanical and aesthetic performance of Flax/PP laminates. The manufacturing and environmental variables have been sequentially investigated to identify a cumulative improvement on the performance of the Flax/PP composites. Temperature and dwelling time were the parameters with greatest influence on the aesthetics and mechanical performance of the Flax/PP. The thermoforming pressure and the size of the manufacturing area were the parameters that contributed the less. Although the moisture absorption degraded the Flax/PP mechanical performance, the moisture desorption had however a negligible impact. We therefore conclude that Flax/PP thermoformed parts could be suitably produced and stored in normal room conditions.

Keywords: A. Thermoplastic resin, B. Wettability, D. Mechanical testing, E. Compression moulding, Wood plastic composites (WPC)

1. INTRODUCTION

The use of bio-composite materials is becoming more widespread due to new regulations that foster the use of more sustainable and recyclable materials[1]. The automotive industry is focused in particular on the adoption of cost-effective and lightweight materials. Because of this, bio-composites are used in many secondary automotive applications[2, 3]. Bio-composite materials begin also to show some promising mechanical performances for more focused structural applications[4].

Bio-composites are defined by the inclusion of one or more materials obtained from natural sources (animals or plants). Those materials act as fibres, matrices or fillers. Polylactic acid (PLA) is an example of a bio-matrix extensively investigated by many researchers and widely used in the 3D printing industry[5]. Polypropylene (PP) matrices are also being developed from natural resources and are considered economically attractive for commercial productions[6]. A subset of bio-composite materials developed since the 1970s is the one related to wood plastic composites (WPCs). Wood plastic composites consist of reinforcing plastics with plant sourced fibres or fillers[7]. WPCs are currently receiving a significant amount of interest, and several research and development programs are dedicated to improve their specific physical and chemical performance[8]. An example of the significant academic interest in the field is the growing number of publications dedicated to the mechanical characterization of natural fibres, from the six published in 1998 to 239 that appeared in international journals during 2018[9].

Since natural fibres are sourced from plants, variations of the physical and chemical compositions are present in derived yarns, fabrics and composites[10]. The variation in performance is a result of variable difficult to control variables, like the plant growth conditions and the extraction method of the fibres[11]. In addition, the performance of natural fibres is significantly affected by other controllable parameters, such as storage conditions, humidity levels and matrix compatibility[12]. Thermoplastic WPC processing involves the use of parameters that impact significantly on the performance of those composites, such as the temperature, the dwell time and the pressure[13]. Furthermore, thermoplastic WPC fabrication techniques have a direct impact on the mechanical performance, as also demonstrated in open literature[14-17]. There is therefore the need of pursuing further research and development activities to analyse the impact of those factors on the performance of WPCs and to enable their wider use in engineering applications.

Flax fibres extracted from the plant's bast are a good example of natural reinforcements that have been historically used within many industries[18]. Flax fibres make up half of bio-based reinforcements used in automotive applications, followed by kenaf and hemp[19]. In other industries designers are starting to notice the

capability of Flax fibres to replace E-glass reinforcements for lightweight applications[20] and also enhance the vibration damping of carbon fibres composites through hybridization concepts[21]. In general, Flax fibres are however recommended for designs dominated by stiffness rather than ultimate strengths[22].

Among the main concerns about the performance of WPCs is moisture absorption. The mechanical performance of wood polymer composites deteriorates with moisture, and this is explained by the swelling of fibres that initiate micro cracks in the matrix and by the growth of rot due to the immersion in water for prolonged times[23]. Moisture also impacts the aesthetics of natural fibres by darkening their colour[24], swelling their cross section and increasing their surface roughness[25]; these effects are still present in WPCs derived by the use of the natural reinforcements. These issues could be tackled by applying a chemical treatment to the fibres or to the matrix, however this would add more costs and difficulties to the manufacturing process[26, 27].

Thermoplastics WPC is found to be significantly affected by the prolonged exposure to high temperature levels during manufacturing, which cause the thermal degradation of both fibres and matrix. Velde and Kiekens[28] studied the effect of a combination of hot and cold pressing temperatures, duration time and fibre treatments on the flexural performance of non-woven Flax/PP WPCs. They controlled the movement of the press movement by monitoring the thickness of the produced laminate rather than the value of the applied pressure. Their study indicates that 200 °C and 3.5 mins are the optimum fabrication parameters in term of flexural performance, however the same Authors could not draw a clear conclusion about the effect of the fibre treatment because they used fibres from different sources. Kim and Park[29] have developed a direct impregnation technique for the thermoplastic melt fabrication method of Flax/PP WPCs using a fixed depth mould, and they obtained comparable results with other studies. In their work thermoforming at 215 °C for a duration of 4 mins and a late gradual increase of the pressure provided samples with the best flexural performance. These two studies suggest a particular route and tools to obtain Flax/PP composites at the highest processing temperature. Ramakrishnan et al[30] carried out a sensitivity analysis on the tensile and vibration damping performance of twill woven commingled Flax/PP laminates considering the hot-press fabrication temperature, pressure and dwelling time as parameters. They showed that a specific combination of fabrication parameters (200 °C, 4 MPa and 5 min of dwelling time) gave them the optimum tensile performance; the vibration damping analysis however is not conclusive. As a general guideline, the temperature to process Flax fibres should not exceed 230 °C to mitigate the deterioration of the performance of these plant reinforcements[31].

This study is dedicated to analyse the mechanical tensile and flexural behaviour of Flax reinforced PP composites produced using different thermoforming fabrication parameters. Twelve laminates of Flax/PP WPC were thermoformed using a hot-press and examined mechanically and aesthetically. The Flax/PP laminate with the best performance observed during the mechanical tests was used to analyse the influence of the humidity sorption on its behaviour. During the initial steps in the study, adding end tabs to the tensile samples of Flax/PP was found to be not required based on the results. As expected, the results mainly highlight the high dependency of Flax/PP WPCs mechanical and aesthetic characteristics on the thermoforming parameters, which shows the adaptability of the material to a wide range of applications. Likewise, the Flax/PP WPC performance is also significantly affected by the environmental humidity levels, which contribute to deteriorate the mechanical performance and change the aesthetics of the composites, making them particularly unsuitable for marine applications.

2. MATERIALS, FABRICATION AND TEST PREPARATION

In this work the composites have been produced using Biotex Flax fabric (EasyComposites™). The fabric has been stored at controlled at room conditions of 20°C and 45% humidity level. The Flax fabric is in 4X4 plain weave form (Figure 1) with 7 ends/cm and 11 picks/cm in warp and weft directions, respectively, and surface weight of 500g/m². The Flax fibres have not been subjected to any surface treatment, but the tows are commingled with PP fibres, and this produces laminates of 40% fibre volume fraction and density of 1.04 g/cm³, as per the producer's material data sheet. Each Flax tow has two threads of PP, one in between the Flax fibres and another curled around the same fibres to make a stable tow (Figure 2).

Flax/PP laminates of 3 layers and 30*30 cm² dimensions have been thermoformed using a hand layup and a HARE Ltd hot-press that has the capability of reaching 200°C and 50tons. The thermoforming procedure is controlled by manipulating five parameters: the highest temperature and its dwelling time, the applied pressure, the weave direction and the size of the area of the laminated fabric. A parametric study has been carried out based on the assumption that the parameters are statistically uncorrelated between each other. All the fabricated laminates with the altered thermoforming parameters are summarized in Table 1.

The mechanical characterisation of the laminates has been performed using a Shimadzu mechanical testing machine with two load cells of 10 kN and 1 kN maximum loads to carry out tensile and flexural tests, respectfully. The tensile tests have been executed following the guidelines of the D3039 ASTM standard[32], with a velocity of the cross-head of 3mm/min and the use of self-aligning fixtures. In addition, the effect of the samples end-tabs on the test results has also been evaluated. Flexural tests have been performed according to the D7264 ASTM

standard[33] in 3-points bending mode with a rate of the cross-head of 1mm/min, and thickness to span ratio of 32. The comparison between laminates is based on the values of the ultimate stress and strain and modulus of elasticity. In addition, the water uptake and the effect of moisture on the mechanical performance of the optimum laminate have been evaluated following the D570 ASTM standard[34].

3. HOT-PRESS THERMOFORMING CYCLE

The hot-press used in this study lacks a cooling stage and has only base functions to control the pressure, temperature, heating rate and dwelling time. For simplicity, the thermoforming cycle has been started from cold ($\sim 25^{\circ}\text{C}$) with the fastest rate possible ($\sim 10^{\circ}\text{C}/\text{min}$), and ended at an easy-to-handle temperature ($\sim 70^{\circ}\text{C}$) without pre-heating or cooling. During the thermoforming cycles variations of ± 1 tons can be observed in the hot-press pressure gauge. The temperature profile has been recorded using thermocouples that record the temperature of the top and bottom hot-press plates every second. Figure 3 shows some typical thermoforming cycles with the temperature values, and the programmed pressure levels. The hot-press tends to over-heat the components in order to maintain the temperature for the programmed dwelling time (Figure 4), and that created a discrepancy between programmed and actual dwelling times (Table 2). It is therefore strongly advised before using any hot press for large volume productions to first record the actual temperatures existing on a sample laminate and decide if it is suitable for the constituent materials or not. Concerning the materials and the hot-press used in this work, it was found that it is possible to thermoform the best Flax/PP laminate within the operational temperature range and programmed variables of the hot-press facility, as it will be demonstrated in the following paragraphs. Table 2 also shows the actual dwelling time as the time interval during which the temperature was above the programmed temperature value.

4. RESULTS AND DISCUSSIONS

4.1. FABRICATION OF THE LAMINATES

The topography of the laminate is a good illustrator of the state of the fibres and the matrix with the various manufacturing parameters. There are five features that can be easily observed subjectively by the naked eye: the surface roughness, the fibres tension, the tows warpage, the fibres wettability and the colour of the laminate. Surface roughness and fibres wettability show slight improvements after 185°C , and after 160sec of dwelling. No change of features is however observed with the increase of the applied pressure. The warpage of the tows and the tension of the fibres continue to be more evident with higher values of the fabrication parameters (Table 3). These two observations (longer dwelling times and higher applied pressure) indicate that the matrix becomes

highly viscous at 175°C, and it dislocates the fibres during its outward movement (Figure 5). The colour of the laminates becomes slightly darker with longer dwelling times, significantly darker at the highest temperature considered here[29] and appears to be virtually unchanged by applying higher pressures (Table 3). The higher temperature makes the matrix less viscous[35], and that causes a non-uniform dislocation of the fibres, hence the formation of matrix-rich areas. The change in the colour of the laminate suggests the existence of fibres and matrix degradation at high temperatures and longer dwelling times. The change of the weave direction on the laminated area does not however have an effect on the topology of the laminate, except for the warpage of the tows that worsens by increasing the laminate area due to the presence of more matrix moving around. The shade of Flax fibres could act as an indicator of the water uptake[24]; the laminate becomes darker with the increased moisture content.

In addition to the subjective characterisation, the thickness of the laminates and their density were measured. The laminates thickness has an intuitive opposite relation with the dwell time, pressure and temperature variables (Figure 6); the thickness is heavily affected by the moisture uptake -increasing by 12.4% for an 8.9% weight increase-. Likewise, the density of the laminates shows a positive relation with all the manufacturing variables in this study (Figure 7). Although the laminates with the duration time of 1280 seconds had a density average lower than the 640 seconds ones, their standard deviations overlap and that makes this a statistically non-relevant observation.

4.2. ANALYSIS OF THE TENSILE END-TABS

According to the ASTM standard tensile test procedure[32], the use of end-tabs is not required as long as the failure happens following some acceptable failure modes and locations with repeatable results. For verification purposes, tensile tests have been carried out on Flax/PP samples with and without end-tabs made from glass fibre reinforced epoxy. The tensile results in Figure 8 show a negligible influence provided by the presence of the tabs on the Flax/PP performance. The carried tensile tests had however low loading levels (around 1.4kN), and that is believed to minimize the effect of the testing machine grips on the failure mode and its location on the samples due to the lower induced gripping stresses. The following tensile tests have been then carried without the use of end-tabs to the samples. Evidently, Figure 8 shows the typical bilinear behaviour of Flax composite materials reported in the literature[36]. This behaviour is believed to be caused by the elementary Flax fibres' kink band defects and micro fibril angle rotation inherited mainly from extraction and weaving methods of the fibres.

4.3. ANALYSIS OF THE FABRICATION HIGH-TEMPERATURE DWELLING TIME

The laminates manufactured at 175°C and 3.7 MPa have been characterized mechanically using tensile and flexural tests (Figure 9 and Figure 10). In general, the tensile and the flexural performances show similar trends versus the increase of the high-temperature dwelling. Higher high-temperature dwelling times facilitate the melting of the polypropylene yarns and the flow of the thermoplastic material between the Flax fibres, providing an improved consolidation of the laminate and surface finish, with positive effects on the load transfer capability. The matrix flow also causes the fibres to minimize their waviness and therefore improves the load bearing efficiency. On the opposite, one can observe a drop in the mechanical behaviour after the long exposure to the highest temperature for 1280sec; this is believed to be caused by the degradation of the fibres and the matrix. Meanwhile, the higher error in the results related to the longest dwelling times is caused by the fibres tow warpage at the edges of the laminate caused by the outward movement of the high viscosity polypropylene. This makes the orientation of the fibres not consistent across the samples cut from the laminates.

The tensile results in Figure 9 exhibit a bilinear behaviour, and this is more evident in the samples with the lower dwelling times. The first segment of the stress-strain curves (up to 0.5% of elongation) is representative of the matrix-dominated behaviour of the laminates. The second segment is representative instead of the fibres-dominated behaviour. At lower dwelling times, the fibres have more freedom to gradually separate and pull-out before failure, the latter caused by lower matrix consolidation levels. A similar behaviour is also evident in the flexural curves (Figure 10), in which short dwelling times lead to a more gradual failure. The level of the matrix consolidation is observed clearly in Figure 11, in which images of samples after failure with different dwelling times are shown. Under tensile loading, fibres and yarns are completely separated from each other; this is particularly evident in the case of short dwelling times, for which the areas with evidence of failure are also larger than in the long dwelling time case. Samples subjected to bending features some apparent cracks in samples with long dwelling times. Specimens with short dwelling times feature instead permanent deformations without visible cracks. Moreover, the standard deviation of the values related to every mechanical property of the samples becomes larger with the increased dwelling times, and this is caused by the misalignment of the yarns during the melt flow movement of the PP (Table 4). In conclusion, the laminates manufactured in this work with 640 sec of dwelling time, thermoformed at 175°C with a 3.7 MPa pressure feature the combination of best mechanical properties.

4.4. ANALYSIS OF THE LAMINATES SURFACE AREA AND WEAVE ORIENTATION

Figure 12 and Figure 13 show the effect of the change of laminated area and weave orientation on the tensile and flexural properties. By laminating smaller fabric surfaces one can reduce the amount of polypropylene and the quantity of fibres obstructing the matrix flow and produce lower internal forces that straighten the fibres during the thermoforming cycle. These effects contribute to increase the load bearing capability of the fibres. On the other hand, larger laminated areas will produce more variation in the fibres' alignment and pretension between the edge and inward yarns, especially for laminates with higher matrix consolidation levels. The fabric preform used in this study has more fibres in the weft direction than in the warp one, which -as expected- translates in higher stiffness and strength along the weft direction, as observed from the figures. In general, the change of the laminated area or the weave direction have negligible impact on the aesthetics of the composite (Table 3) and its failure mechanism (Figure 11.B). The ultimate mechanical properties of the samples are listed in Table 5. The optimum conditions in this analysis appear to be the use of a small laminated surface to consume less material, and the aligning of the weft direction of the fabric along with the applied load direction.

4.5. ANALYSIS OF THE FABRICATION PRESSURE

The level of pressure used during the thermoforming process is found to affect the mechanical performance of Flax/PP WPC (Figure 14 and Figure 15). More pressure will benefit the tensile and flexural behaviour of the WPC laminate by inducing more stretch on the Flax fibres and more compactness layers-wise, although the latter is more evident under tension. On the other hand, the variation of the pressure fabrication does not affect the failure mechanism due to tensile or flexural loadings; all the samples exhibit a similar failure behaviour to the one shown in Figure 11.B. The analysis of the thermoforming pressure suggests using higher pressure levels to obtain enhanced mechanically performing laminates (Table 6).

4.6. ANALYSIS OF THE FABRICATION TEMPERATURE

Four temperature levels have been here considered to evaluate the impact of the manufacturing temperature on the mechanical properties (175, 185, 190 and 200 °C). Thermoforming Flax/PP laminates at high temperatures (+185°C) improves significantly both the mechanical performance and the aesthetic of the laminates. Figure 16 and Figure 17 show the Flax/PP behaviour under tensile and flexural loading versus the different temperatures considered here, and 3.7 MPa of pressures and 40s of dwelling time. Although the fabricated Flax/PP at 185°C showed here the highest ultimate properties in both flexural and tensile loading, those laminates were also more compliant than the composites produced at 190°C and 200°C at low tensile strains. A stiffer tensile response at lower strains is likely due to the improved coupling between the Flax fibres and the PP matrix. At higher

temperatures the thermoplastic matrix becomes less viscous, and that facilitates the flow between the fibres which have improved laminate's consolidation when it cools down. At the same time, higher temperatures cause a degradation of the natural fibres[28], leading to failure at lower stress levels. The optimum fabrication temperature in this analysis is 185°C based on the ultimate mechanical properties presented in Table 7.

4.7. ANALYSIS OF THE MOISTURE UPTAKE

Natural fibres' moisture uptake and release rate and magnitude are much higher than thermoplastics in general[26]. This is facilitated in WPC by samples edges which expose the fibres to the elements, making the matrix contribution to moisture content to be negligible[37]. After conditioning Flax/PP samples in an oven for 24 hours at 50°C following D570 ASTM standard, it lost 1.1% of its weight due to moisture desorption. This however is less than what other study found when they dried Flax fibres at 105 °C for 14 hours losing 6.2% of its weight; a method dictated by their TGA analysis results[38]. The difference is believed to be related to the much higher temperature used and the amount of Flax directly exposed to the environment which make moisture release much easier. Even though the average curves in Figure 18 and Figure 19 show that dry Flax/PP samples have a lower mechanical response to the normal samples, both results fall in each other standard deviation values rendering the difference to be insignificant. Furthermore, losing 1.1% of Flax/PP samples normal weight in moisture desorption stage did not affect its dimensions. This indicates the suitability of storing, fabricating and using the Flax/PP in normal room conditions.

Flax/PP weight was found to have 2.7% increase after submerging in distilled water for two hours. Immersing Flax/PP samples in water for 24 hours increased the thickness of the samples by 12.4% which had a significant impact on their performance. A water uptake of 8.5% contributed to dramatically decrease the flexural strength by ~50% and the flexural stiffness by ~70%. Although the tensile stiffness decreased by ~60%, the tensile strength had however a 13% improvement after the water uptake. The deterioration of the mechanical properties is expected because of the swelling of the fibres caused by the moisture absorption, which will initiate microcracks in the matrix and facilitate the fibre/matrix debonding. In addition, the moisture made the Flax/PP more flexible allowing it to strain ~70% more than the normal conditioned samples before failure under tensile or flexural loading would occur. Flax fibres appear to gain more tensile strength after the water uptake, which requires a more dedicated study on the individual fibre scale. Table 8 list the ultimate mechanical properties for the Flax/PP in the three tested states: dry, normal and wet conditions.

5. UNIVERSAL TENSILE AND FLEXURAL ANALYSIS

The best results of this study are shown in Figure 20, and they are based on specific strength and stiffness measured from the Flax/PP WPC tensile and flexural tests. In the fabric warp direction, the decrease of the thermoforming pressure and dwelling time while increasing the temperature positively impacts the mechanical properties. Whereas in the weft direction, although the tensile behaviour appears to be not affected by the shortened dwelling time and the increased pressure and temperature values, the flexural performance has significantly improved following the variation of those fabrication parameters. Looking at Figure 20 as a whole, it can be clearly observed that the alignment of more fibres towards the applied load will benefit the WPC performance, and this regardless of the other fabrication parameters. Also, by applying a greater thermoforming pressure one would affect the flexural performance more than the tensile behaviour. Moreover, the WPC tensile properties displayed a higher sensitivity to the fabrication pressure when less fibres were parallel to the loading axis.

Specific mechanical properties of this study Flax/PP WPC are compared with literature in Figure 21. Current WPC results show superior stiffness performance to Glass/PP, which supports the finding of Shah study where stiffness dominated application is more suitable for Flax WPC. On the other hand, current study exhibits inferior strength performance to the other studies. These observations can be impacted by many variables such as fibres length and preform, fabrication method and Flax fibres inherited qualities, which would be difficult to quantify here.

6. CONCLUSIONS

Flax fibres reinforced polypropylene WPC were found to be sensitive to the fabrication parameters, in particular, to the top thermoforming temperature. Similarly, the elevated level of moisture in Flax/PP WPCs has a large negative impact on the tensile and flexural performance of the laminates. However, materials storage and fabrication environment conditions of the Flax/PP WPC were found to have negligible effect on their behaviour.

Simple observations of the colour, fibres tensions and warpage of the Flax/PP laminates provide some sufficient initial indications on the suitability of the chosen thermoforming process before carrying more systematic experiments. High levels of tension and warpage of the fibres indicate a matrix with a high viscosity being moved for a long time or forcefully, while a dark colour of the laminates points to excessive temperatures applied. Thus, a balance between the thermoforming dwelling time, pressure and temperature needs to be achieved to minimize the tension and warpage of the fibres without darkening significantly the colour of the laminates.

Thermoforming tools greatly differ in terms of thermal conductivity and that requires a closer look to verify the actual temperature effectively occurring within the fabricated laminate. The use of a thermoforming cycle with an active cooling stage is recommended for a higher control quality of the produced WPCs.

Although the laminates manufactured in this work are representative of laboratory conditions, the results nonetheless provide a good indication about how to tailor a possible bespoke mechanical performance in Flax/PP WPCs.

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Table 1: Thermoforming parameters of all Flax/PP laminates

#	TEMPERATURE °C	DWELL SEC	PRESSURE MPa	WEAVE DIRECTION	AREA %
1	175	40	3.7	Warp	100
2	175	160	3.7	Warp	100
3	175	640	3.7	Warp	100
4	175	1280	3.7	Warp	100
5	175	640	3.7	Warp	75
6	175	640	3.7	Weft	75
7	175	640	2.7	Warp	75
8	175	640	4.7	Warp	75
9	185	40	3.7	Warp	75
10	190	40	3.7	Warp	75
11	200	40	3.7	Warp	75
12	185	40	4.7	Weft	75

Table 2: Hot-press input and actual thermoforming parameters

PROGRAMMED VALUES		ACTUAL VALUES	
HIGHEST TEMPERATURE °C	DWELLING TIME SEC	HIGHEST TEMPERATURE °C	DWELLING TIME SEC
175	160	187.5	570
175	640	187.8	660
175	1280	188.5	700
175	40	179.8	210
185	40	189.4	188
190	40	194.2	184
200	40	204.3	185

Table 3: All Flax/PP fabricated laminates

ANALYSIS TYPE	LAMINATE			
DWELLING TIME	40 sec	160 sec	640 sec	1280 sec
AREA AND WEAVE	100%	75% Warp	75% Weft	
PRESSURE	2.7 MPa	3.7 MPa	4.7 MPa	
TEMPERATURE	175°C	185°C	190°C	200°C
MOISTURE	Dry	Normal	Wet	

NOTE: PICTURES MIGHT HAVE DIFFERENT HUE DUE TO LIGHTING CONDITIONS

Table 4: High temperature dwelling time effects on the ultimate mechanical properties of the Flax/PP WPCs

LAMINATE	ULTIMATE TENSILE PROPERTIES			ULTIMATE FLEXURAL PROPERTIES		
	Stress (MPa)	Strain (%)	Young's Modulus (GPa)	Stress (MPa)	Strain (%)	Young's Modulus (GPa)
40 SEC	33.47 ± 2.09	7.39 ± 0.57	2.85 ± 0.06	26.53 ± 4.77	3.46 ± 0.33	1.88 ± 0.35
160 SEC	38.38 ± 2.35	2.23 ± 0.20	4.54 ± 0.31	59.17 ± 2.30	3.55 ± 0.16	4.98 ± 0.32
640 SEC	58.39 ± 6.81	1.55 ± 0.18	6.34 ± 0.79	78.63 ± 3.82	2.63 ± 0.09	7.19 ± 0.25
1250 SEC	47.37 ± 5.10	2.41 ± 0.23	4.60 ± 0.37	75.17 ± 3.85	2.84 ± 0.19	6.54 ± 0.17

Table 5: Area size and weave direction effect on ultimate mechanical properties of Flax/PP WPC

LAMINATE	ULTIMATE TENSILE PROPERTIES			ULTIMATE FLEXURAL PROPERTIES		
	Stress (MPa)	Strain (%)	Young's Modulus (GPa)	Stress (MPa)	Strain (%)	Young's Modulus (GPa)
100% WARP	58.39 ± 6.81	1.55 ± 0.18	6.34 ± 0.79	78.63 ± 3.82	2.63 ± 0.09	7.19 ± 0.25
75% WARP	54.31 ± 3.59	2.20 ± 0.27	4.92 ± 0.18	70.93 ± 2.27	2.90 ± 0.10	6.44 ± 0.40
75% WEFT	76.13 ± 2.31	2.37 ± 0.09	6.29 ± 0.21	83.70 ± 3.66	3.12 ± 0.19	7.79 ± 0.61

Table 6: Fabrication pressure effect on ultimate mechanical properties of Flax/PP WPC

LAMINATE	ULTIMATE TENSILE PROPERTIES			ULTIMATE FLEXURAL PROPERTIES		
	Stress (MPa)	Strain (%)	Young's Modulus (GPa)	Stress (MPa)	Strain (%)	Young's Modulus (GPa)
2.7 MPA	50.02 ± 2.74	2.32 ± 0.17	4.56 ± 0.15	68.10 ± 4.22	3.13 ± 0.13	6.06 ± 0.42
3.7 MPA	54.31 ± 3.59	2.20 ± 0.27	4.92 ± 0.18	70.93 ± 2.27	2.90 ± 0.10	6.44 ± 0.40
4.7 MPA	59.12 ± 1.23	2.05 ± 0.10	5.36 ± 0.07	72.87 ± 4.68	2.83 ± 0.20	6.62 ± 0.47

Table 7: Fabrication temperature effect on ultimate mechanical properties of Flax/PP WPC

LAMINATE	ULTIMATE TENSILE PROPERTIES			ULTIMATE FLEXURAL PROPERTIES		
	Stress (MPa)	Strain (%)	Young's Modulus (GPa)	Stress (MPa)	Strain (%)	Young's Modulus (GPa)
175°C	33.47 ± 2.09	7.39 ± 0.57	2.85 ± 0.06	26.53 ± 4.77	3.46 ± 0.33	1.88 ± 0.35
185°C	63.65 ± 3.18	2.36 ± 0.19	5.36 ± 0.21	76.17 ± 4.47	2.90 ± 0.04	7.22 ± 0.60
190°C	58.32 ± 2.11	1.79 ± 0.16	5.51 ± 0.21	71.61 ± 3.22	2.57 ± 0.18	6.81 ± 0.29
200°C	59.48 ± 3.02	1.92 ± 0.14	5.52 ± 0.4	71.42 ± 4.76	2.58 ± 0.24	7.25 ± 0.28

Table 8: Moisture effect on ultimate mechanical properties of Flax/PP WPC

SAMPLES	WIEGHT	ULTIMATE TENSILE PROPERTIES			ULTIMATE FLEXURAL PROPERTIES		
	Increase (%)	Stress (MPa)	Strain (%)	Young's Modulus (GPa)	Stress (MPa)	Strain (%)	Young's Modulus (GPa)
DRY	Reference	70.40 ± 6.03	2.05 ± 0.07	5.01 ± 0.62	85.72 ± 8.90	2.09 ± 0.10	8.67 ± 1.29
NORMAL	2.7	76.07 ± 4.86	2.20 ± 0.13	6.23 ± 0.17	91.39 ± 3.48	2.34 ± 0.19	9.22 ± 0.41
WET	8.5	82.35 ± 5.21	3.82 ± 0.13	2.49 ± 0.07	47.85 ± 3.45	3.93 ± 0.16	3.06 ± 0.13

Figure 1: Flax/PP fabric

Figure 2: Flax and PP yarn

Figure 3: Typical hot-press thermoforming temperature and pressure profiles. Blue: pressure, orange: temperature

Figure 4: Hot-press highest temperature profiles

Figure 5: Dislocation of flax yarns during the thermoforming process

Figure 6: Thickness of fabricated Flax/PP laminates

Figure 7: Density of fabricated Flax/PP laminates

Figure 8: Tensile results of samples with and without end-tabs

Figure 9: Tensile results of different dwelling time laminates manufactured at 175°C and 3.7MPa

Figure 10: Flexural results of different dwelling time laminates manufactured at 175°C and 3.7MPa

Figure 11: Dwelling time effect on tensile and flexural failure;
A)20 sec laminate B)640 sec laminate

Figure 12: Tensile results of different laminated area and weave manufactured at 175°C, 3.7MPa and 640sec

Figure 13: Flexural results of different laminated area and weave manufactured at 175°C, 3.7MPa and 640sec

Figure 14: Tensile results of different pressure laminates manufactured at 175°C and 640sec

Figure 15: Flexural results of different pressure laminates manufactured at 175°C and 640sec

Figure 16: Tensile results at different temperatures of laminates manufactured at 3.7MPa and 40sec

Figure 17: Flexural results at different temperatures for laminates manufactured at 3.7MPa and 40sec

Figure 18: Tensile results of different conditioned samples at 185 °C, 3.7MPa and 40sec

Figure 19: Flexural results of different conditioned samples at 185 °C, 3.7MPa and 40sec

Figure 20: Flax/PP WPC tensile and flexural specific results

Figure 21: Comparison of mechanical properties studies

Source for figure 21, to update reference in the table