Article

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External compaction pressure over vacuum-bagged composite parts: Effect on the quality of flax fiber/epoxy laminates

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Abstract

Vacuum bagging allows the removal of trapped air between fabrics layers, extraction of moisture and volatiles, and optimization of the fiber-to-resin ratio. However, during vacuum bagging the compaction pressure is limited to atmospheric pressure, preventing the composite reaching higher fiber volumetric contents and also allows surface porosity to arise, affecting the esthetical appearance of the composite and also its mechanical performance. While the autoclave process has shown to solve these problems, the cost of the equipment is too high for many applications. In the present work, a series of experiments are carried out by compressing unidirectional flax/epoxy vacuum-bagged laminates in a hydraulic press at different pressures. The quality of the laminates is analyzed in terms of surface finish, internal void content, and mechanical properties. The additional compaction from hydraulic pressure is shown to be very effective in improving considerably the overall quality of the composites.

Keywords

Polymer composites, flax fiber, mechanical properties, porosity/voids, vacuum bagging, compression molding

Introduction

The hand layup technique is the simplest and least expensive manufacturing method for composite material parts. The quality of the laminates obtained by this method is usually poor, since the absence of compaction pressure on the laminate leads to low fiber volumetric fractions and also high amount of porosity in the composite microstructure. This porosity can be generated by entrapped air during the wetting stage of the process, air bubbles present in the resin, or by volatiles generation prior and during curing. The improvement in the mechanical performance of composite materials by increasing the fiber volumetric content has been reported by many authors[1,2] and the detrimental effect of voids on the mechanical performance of composites can be also found in literature.[3–5] Therefore, in order to obtain composite materials with enhanced properties, more complex manufacturing techniques have to be used, such as vacuum infusion and vacuum bagging. Despite being quite different, these two techniques allow to apply compaction pressure (via vacuum pressure) to consolidate plies; decrease the amount of excess resin; and extract moisture, solvents, and volatiles from the curing composite. Both techniques utilize a one-sided mold with bagging film being utilized for the other side, which is sealed to the rigid mold with a rubberized tape. The main difference between both techniques is the impregnation method: in vacuum infusion the preform is a dry stack of fabrics and the resin is sucked into it by the applied vacuum, impregnating the fibers; while in vacuum bagging the part is hand laminated. In order to extract the excess resin present due to the hand lamination process, a bleeder cloth is used over the preform. In addition, a porous film (a perforated plastic film) is used between the bleeder layer and the wet

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laminate in the vacuum bagging process to control the resin flow from the part to the bleeder cloth. A "peel ply" is used in both methods to peel the consumables off the finished part (vacuum bag, hoses, porous film, and bleeder cloth).

Kim et al.[6] showed that vacuum infusion-processed glass fiber-reinforced plastics have higher average ultimate strength and modulus than the same materials processed by hand layup, in both tension and compression tests. They attributed this improvement to the higher fiber volume fraction of the vacuum infusion processed samples. In addition, they also reported an improvement on the shear strength and displacement (maximum reading from extensometer during the tests, in millimeter) over thickness value and concluded that the reason was hand layup's increased porosity. While the vacuum infusion technique is one of the most used for manufacturing large composite structures such as boat hulls and decks, its setup can be too complex for small parts, and the vacuum bagging technique is usually chosen instead. However, as in the vacuum infusion technique, the compaction pressure is limited to the atmospheric pressure, preventing reaching higher fiber volumetric contents. In addition, vacuum bagging wet laminates can generate a high amount of porosity. In these cases, postcure operations like gel coating and painting are needed, which also add weight to the final product as well as time and cost to the manufacturing process. Stringer[7] proved that the viscosity of the resin matrix at the beginning of vacuum bag consolidation is the critical parameter in the fabrication of low voidage carbon fiber epoxy composites using wet resin techniques. He found that it is necessary to allow the resin viscosity to increase to a certain value by incorporating a dwell period into the cure cycle before applying the consolidation pressure. In this way, overbleeding of resin is reduced and the void content in the part is decreased. However, beyond this window the viscosity is too high to allow sufficient resin to bleed out. In addition, during the curing stage of a vacuum-bagged impregnated laminate, voids can arise due to many other different causes: trapped air during the lamination process, volatiles released by the resin (by-products of polymerization, gas release by residual solvents, vaporized monomers, dissolved air and moisture, degradation by-products, or other impurities/contaminants[8]), moisture present in the fabrics because of plant fiber that can absorb moisture from the environment, and volumetric changes of thermoset resins during cure.[9–11] The resin cures in a geometrically constrained environment within the interstices present between consolidated fibers. The shrinkage of the resin during curing causes tensile stresses to develop. These stresses can surpass the intrinsic strength of the resin at a given time which depends on its degree of conversion. Failure will then occur in the form of voids or cracks, which will remain in the final part.[9]

Some strategies have been reported to be effective for reducing void content and improving the surface quality of composites:

1. In processes where a resin is injected under pressure to a mold cavity, such as resin transfer molding (RTM), an increase in the positive hydrostatic pressure can suppress the volatilization of volatiles and collapse the existing voids.[12,13] However, this strategy is not possible for vacuum-bagged laminates.
2. The concentration of volatile species initially present in the resin also can be reduced prior to injection by vacuum degassing.[14] In the same way, fabrics can be dried to reduce their moisture content prior to the manufacturing stage.
3. Allow the resin viscosity to increase to a certain value by incorporating a dwell period into the cure cycle before applying the consolidation pressure, reducing the risk for resin over bleeding.[7]
4. Haider et al.[15] observed pressure drops due to cure shrinkage in automotive RTM panels and correlated these with an increased surface roughness. Their unsaturated polyester resin exhibited significant cure shrinkage (7–10%), which was successfully compensated by including a thermoplastic low profile additive.

The autoclave process can significantly improve the quality of vacuum-bagged laminates, by adding external compaction pressure on the bag side, increasing the fiber volumetric content (reducing the excess of resin), and decreasing the internal voids and superficial porosity. However, the high costs involved in the autoclave process usually limit its use to the aerospace industry. Nonautoclave cure of bagged laminates will only be successful if the defects normally removed by autoclave pressure are suppressed in the vacuum process and both performance and appearance are comparable to parts processed in the autoclave.[8] Adding external pressure to laminates during curing by mechanical means is one possible low-cost solution suitable for industrial applications, particularly for relatively small flat panels or low complexity composite structures. This could be achieved by a matched mold part used to press the laminate on the side of the vacuum bag as a cheaper alternative to RTM. In this work, the effect of applying different amounts of pressure by mechanical means over a unidirectional flax/bioepoxy vacuum-bagged laminate on the quality of the composites was analyzed. Quality was assessed by mechanical tests, microstructural characterization, and a surface porosity analysis.

Experimental procedure

Materials

Composites were made with a commercially available unidirectional flax fabrics supplied by Lineo (areal weight = 181 g/m^2) and a bioepoxy resin (Greenpoxy 56, Sicomin) which obtains a rate of up to 56% of the molecular structure from plant origin. A multipurpose hardener (series SD 8605) was used leading to a total of 37% of bio-based content in the mixture.

Composite samples preparation

Fabrics were taken from the storage room which is conditioned to 45% relative humidity and 20°C and were not dried prior to composite processing. Flat composite material panels were manufactured by vacuum bagging followed by a compression molding stage in a hydraulic press using different loads. Each layer of fabric (10 layers were used in total) was preimpregnated with matrix material by a hand layup technique (using rollers) on an aluminum plate, taking care to keep practically achievable tolerances on fabric alignment. The peel ply (Econostitch®), porous film (Fibre Glast) and bleeder cloth (Fibre Glast) were placed over the impregnated stack of fabrics and the whole system was sealed with a vacuum bag (Fibre Glast). Full vacuum was applied (−100 KPa) and then the system was compressed in a hydraulic press under 3, 5, and 8 ton of load. Since the dimensions of the preform were 23 cm by 27 cm, giving a total area of 621 cm^2, the effective external compaction pressures on the laminate were 4.7, 7.9, and 12.6 bar. The nomenclature used in this work for the different composites is explained in Table 1.

Figure 1 shows schematically the configuration for the bagging setup. The fabrics were manually impregnated inside a rectangle made with the sealant tape commonly used in vacuum infusion and vacuum bagging processes to avoid resin leakages at the external seal caused by the resin flow and the pressure buildup during the compaction stage. In this way, resin was contained inside the inner rectangle and all the excess resin flow was generated through the porous film toward the bleeder cloth. The vacuum hose was located over the bleeder cloth (acting also as the breather cloth) near one of the edges of the aluminum plate, which was left protruding out of the compaction plates of the hydraulic press during compaction.

Composites were cured under full vacuum (−100 KPa) and the corresponding compaction pressure at room temperature for 24 h. Then the compaction pressure was relieved and the composites were postcured under full vacuum for 8 h at 60°C (as recommended by the resin supplier).

The test samples were cut from the panels by means of a laser cutter device to the required shape and dimensions given by the standards used for the mechanical characterization.

Table 1. Specimens nomenclature.

Name	Processing condition	Total compaction pressure during curing (bar)
VB	Vacuum bagged	1
VB3T	Vacuum bagged, 3 ton compaction	5.7
VB5T	Vacuum bagged, 5 ton compaction	8.9
VB8T	Vacuum bagged, 8 ton compaction	13.6

Surface porosity measurement—Image analysis

The sample panels were scanned for computer image analysis to determine the area fraction of surface-breaking pores. A standard method to enhance the visual contrast of surface-breaking pores on nonwhite surfaces is to apply talc to fill the surface pores prior to scanning,[16,17] including for the characterization of pores in composites.[18] After carefully applying talc to the surface pores, the sample panels were carefully covered with transparent tape for inversion of the sample onto a flatbed scanner. The sample panels were scanned at 600 pixels per inch (approximately 236 pixels per cm) to yield high resolution color images with dimensions of 4964 × 7016 pixels. These image dimensions came from the full-scale resolution of the scanner and contained some spare space in the long dimension of the sample panels. The scanned images were cropped to remove any spare space and the physical edges of the panels to ensure that the resultant images for analysis contained only the sample panel surface. All numerical analyses described hereafter were performed using the Matlab computing environment.[19]

As per Kane et al.[20] a series of standard image processing steps were employed to determine the pore surface area fraction. The 24 bit color images were converted to 8 bit gray-scale images. The pixel frequency histograms of the gray-scale images were inspected and they showed generally good separation of the two peaks representing the lighter colored talc and the darker colored surrounding panel surface. In all cases, a gray-scale luminance value of 0.55 (corresponding to a pixel value of 140) represented a good point of separation, and this luminance level was chosen as a common threshold value to apply to all

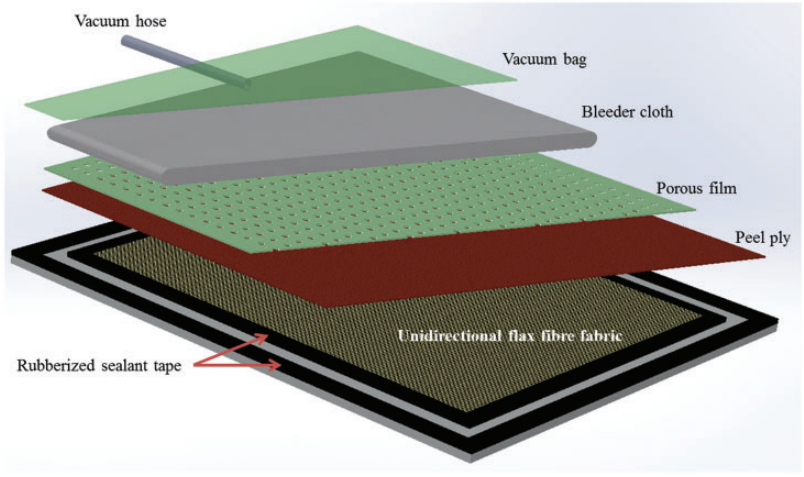

Figure 1. Bagging schedule and processing setup.

images for classification of pixels as either belonging to a pore or part of the surrounding panel surface. Pore surface area fraction in an image was computed as the percentage of the ''white'' pixels in the sum of all (''white plus black'') pixels in an image.

Optical microscopy

Composites microstructure was analyzed by optical microscopy. Transverse sections of the laser cut composites were polished with a 2500 grain size sand paper (SiC) before the microstructural observations.

Mechanical properties evaluation

An Instron universal testing machine was used for the mechanical characterization. Three-point bending tests were performed using a span of 60 mm and a crosshead displacement speed of 2.4 mm/min, according to the ASTM D790-03 standard.[21] Load–displacement curves were obtained from these tests and flexural modulus and strength values were determined. Tensile properties (tensile strength, modulus, and strain at failure) were measured according to the ASTM D3039 standard,[22] using a speed of testing of 2 mm/min. Rectangular specimens were used in both tests. Samples were 250 mm long by 15 mm wide and 80 mm long by 12.7 mm wide, for tensile and flexural tests, respectively. The thickness of each sample was given by the processing conditions (external pressure) and varied from 2.25 mm (highest compaction pressure) to 3 mm (lowest compaction pressure). Five samples were used for each test and the reported results are average values (arithmetic mean), while the error bars shown in the figures correspond to the standard deviation of the set of data values.

Results

Composites final thickness and volumetric fiber content

The reported thickness of the composite panels corresponds to the average value of the thicknesses measured on the test samples before the mechanical characterization. Three measurements were taken along the length of each specimen, and five specimens were used for each test (tensile and flexural) so a total of 30 different measurements were done. The volumetric fiber content was estimated with equation (1), where n is the number of fabric layers, δ is the areal weight of the fabrics (181 g/cm^2), ρ is the flax fibers density (1.45 g/cm^3), and t is the panel thickness (cm).

$$\text{fiber volume fraction } = \frac{n\,\delta}{\rho\,t} \tag{1}$$

Figure 2 shows the thickness and fiber volume fraction obtained with the different external compaction pressures. As expected, the final thickness of the composites decreased and the fiber volume fraction increased, as the compaction pressure applied during the curing stage was increased. It can be seen that the effect of adding 3 ton of load to the vacuum-bagged composites had a significant impact on the fiber volume fraction of the composite, increasing its value 17%. However, the difference observed between samples decreased as the external compaction pressure was increased (10.4% between VB5T and VB3T and 5.7% between VB8T and VB5T). The compaction mechanisms (nesting, yarn bending, yarn flattening, voids condensation within yarns, etc.) that occur during the transverse deformation of the preform become more restricted as the fiber volumetric content increases and

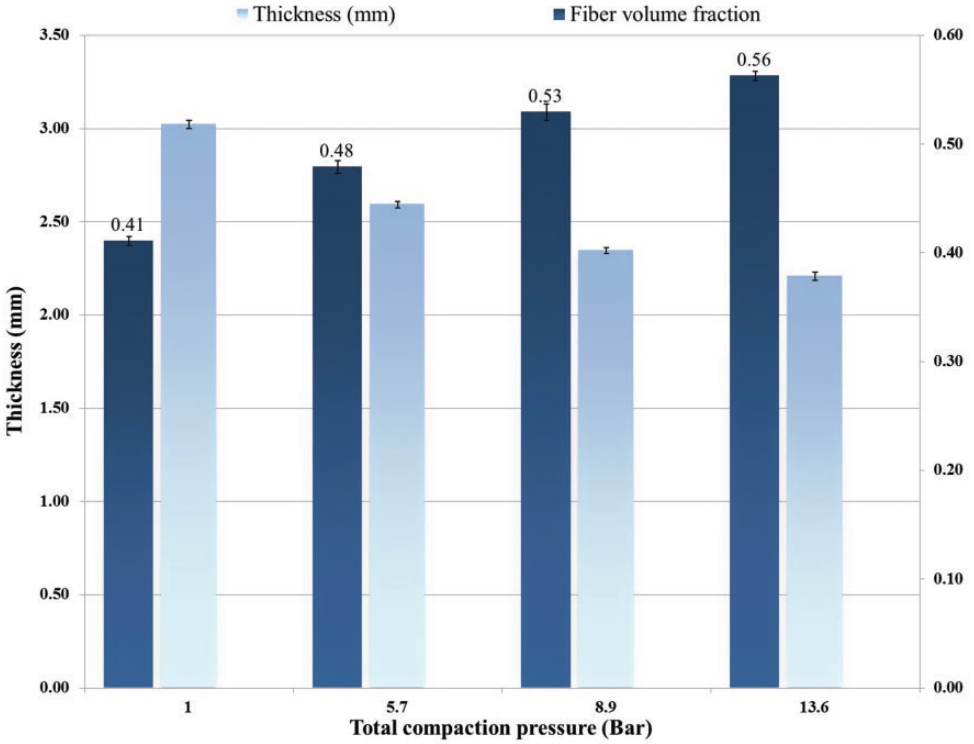

Figure 2. Thickness and fiber volumetric content of the manufactured composites.

thus the change in preform thickness (or fiber content) given by a certain amount of added compaction load is less significant. This observation is consistent with the typical compaction behavior of fibrous preforms reported by many authors.[23–28]

Surface porosity

Figure 3(a) to (d) shows the scanned images of the surface of the composite panels on the aluminum mold side. It can be clearly seen a significant improvement in the quality of the surface by adding external compaction pressure to the laminate. Image analysis results are presented in Figure 4. The highest the compaction pressure used, the better the results in terms of surface quality, but the difference among the three samples subjected to external compaction is quite small in comparison to that observed between the vacuum-bagged composite and the rest. It should be also reported that no significant differences were observed in terms of surface quality on the bag side of the composite panels, which presented a void-free appearance.

The actual causes for the formation of surface voids in the manufactured composites are difficult to determine since there are too many possible sources,[29] as described in the "Introduction" section. Regardless of the origin for this porosity, it was found that the external pressure drastically improved the quality of the surface. One explanation for this observation relies on the resin flow through the preform and the pressure buildup generated inside the inner rectangle where the fabrics were hand laminated (Figure 1). As the hydraulic press compressed the preform, the excess resin was squeezed out of the laminate transporting possible trapped air bubbles present from the hand lamination technique and allowing them to be sucked away by the breather cloth. In addition, this resin was contained by the rubberized sealant rectangle, so the resin pressure gradually increased throughout the laminate, acting in the same way as an increase in the positive hydrostatic pressure during the RTM process. Some of this pressure was slowly relieved by the resin flow through the porous film and subsequent absorption by the bleeder. At some point the bleeder was fully saturated with resin, which could not be extracted through the vacuum hose (resin flow was too slow to allow draining the excess resin out from the bleeder). Therefore, this pressurized excess resin provided a means to suppress the formation of pores due to resin overbleeding, volatilization of species, and also due to curing shrinkage stresses. Another explanation for the improvement in surface quality is that the external compaction load on the fiber stack against the aluminum mold reduced the interstices in-between fibers and in-between yarns at the mold surface, reducing the needed bulk volume. Therefore, the volumetric change due to resin shrinkage

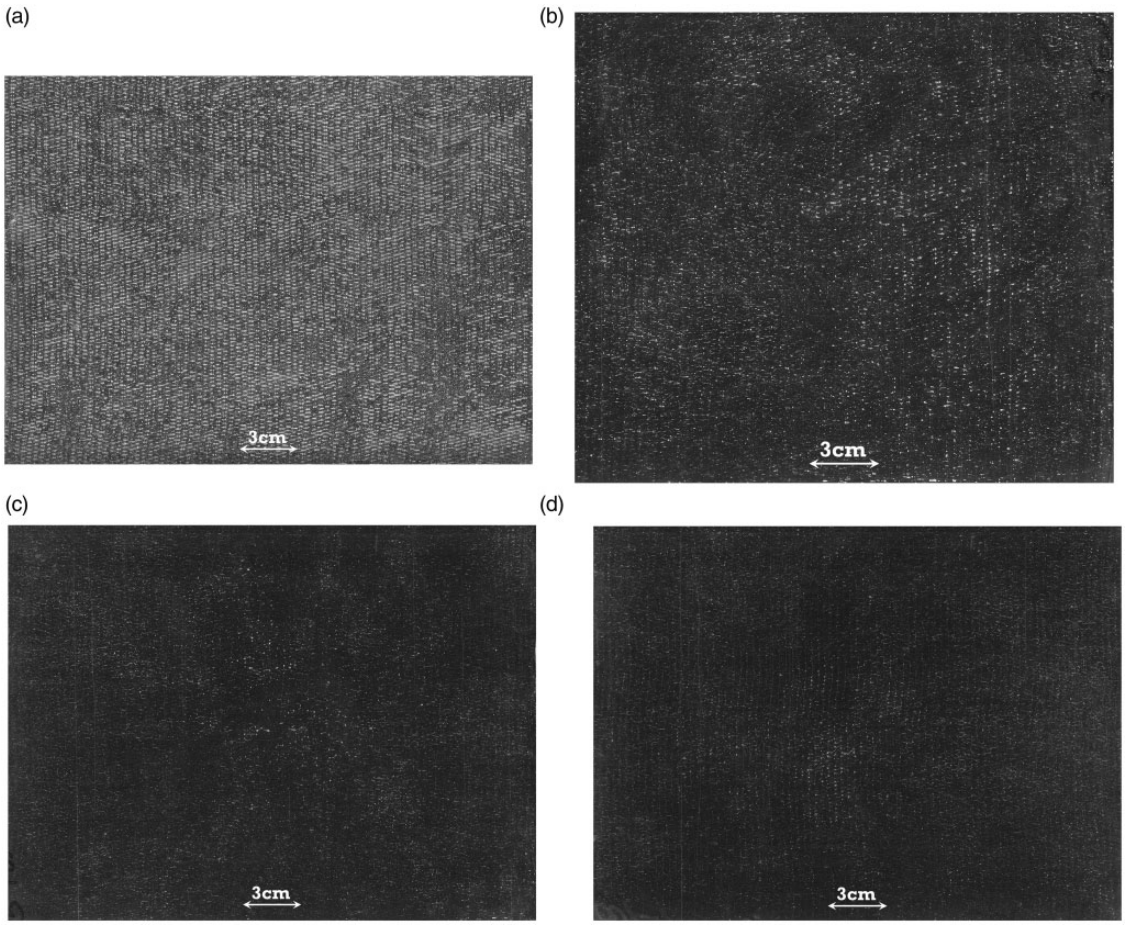

Figure 3. Scans of the mold side surface of the composites. (a) VB, (b) VB3T, (c) VB5T, and (d) VB8T.

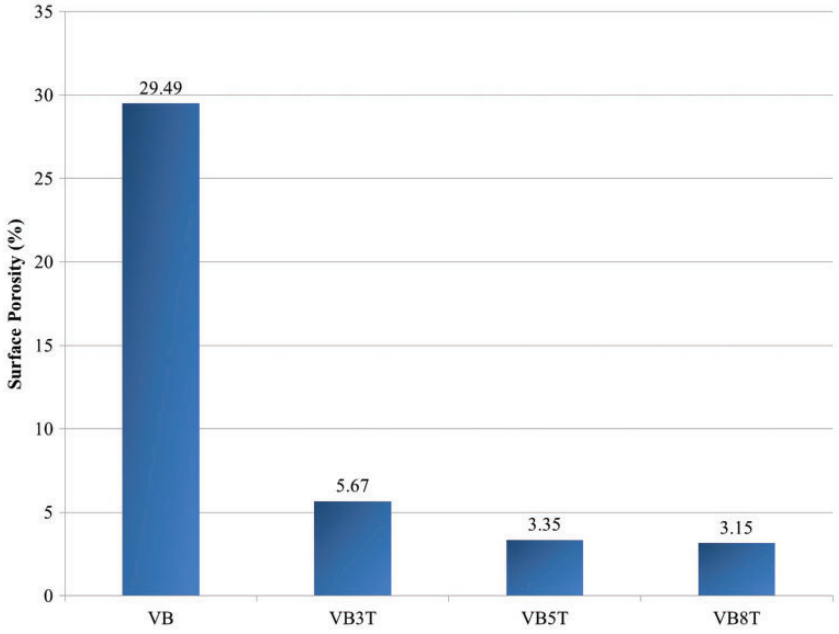

Figure 4. Surface porosity calculated as a percentage of the total panel area.

was not as significant as in the vacuum-bagged composite part, possibly reducing the voids created by this phenomenon.

Microstructural analysis

Figure 5(a) to (d) shows the images obtained by optical microscopy of the transverse section of the flax composite specimens obtained in this work. As expected, it was found that, as the external compaction pressure was increased, the fiber volumetric fraction of the composites increased, as shown in Figure 2. In addition, it can be seen that the VB composites present some noticeable internal voids, while VB3T, VB5T, and VB8T seem to have a much better microstructure. Furthermore, the amount of internal voids decreased as the external compaction pressure on the wet laminate increased. During the hand lamination process done prior to the vacuum bagging, air can be trapped in between fabric layers, which form bubbles that can be evacuated during the vacuum bagging process only if they are transported throughout the laminate and reach the breather layer of the bagging schedule. Big bubbles can get trapped between yarns and these remain in the composite final microstructure. The improvement observed in Figure 5 was clearly caused by the added external pressure acting on the wet laminate before and during cure. As it was explained before, several mechanisms happen during the compaction of the laminate by the hydraulic press that contributes to eliminate trapped internal bubbles:

1. The resin flow through the preform toward its perimeter aids in the transport of air bubbles from the laminate to the breather cloth. In other words, air bubbles are transported at the edges and then upwardly (to the breather cloth).
2. The hydrostatic resin pressure buildup due to pressurized resin inside the mold cavity can collapse bubbles and dissolve volatiles.
3. The external compressive pressure on the laminate directly collapses air bubbles.

Mechanical performance

The flexural strength results are shown in Figure 6, where it can be seen that the composites cured under external compression performed better than the vacuum-bagged composite, showing an increase in strength of approximately 25%. This can be attributed to the better quality (less void content) and improved fiber-to-matrix ratio of VB3T, VB5T, and VB8T. Interestingly, no significant differences could be observed between these three composites in terms of flexural strength. The flexural tests were done on both sides of the composites (porous surface facing upward and downward) to analyze the sensitivity of the properties to the surface porosity, since during the flexural loading one side of the material is under tension and the other one is under compression. It can be seen that if the porous surface is the one loaded under tension, the strength of the composite decreases. Pores act as flaws, being detrimental to the composite strength since they can weaken the material by providing crack initiation sites, as it was demonstrated by Varna et al.[3] The percentage difference on this property measured on both sides can be seen in Figure 7. As expected, VB composites showed a higher sensitivity to the tested side, displaying almost a 5% difference between the strength measured on the "good" side and the porous side, while in the other composites this difference was almost 2%. However, the difference between the

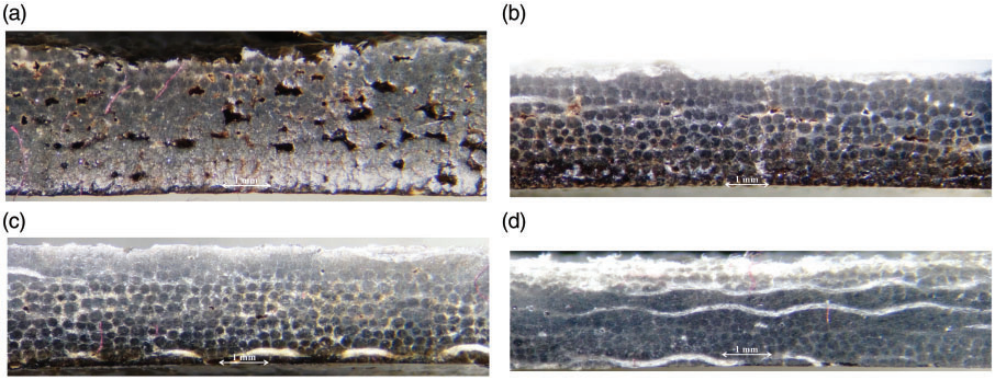

Figure 5. Micrographs of the composites. (a) VB, (b) BV3T, (c) VB5T, and (d) VB8T.

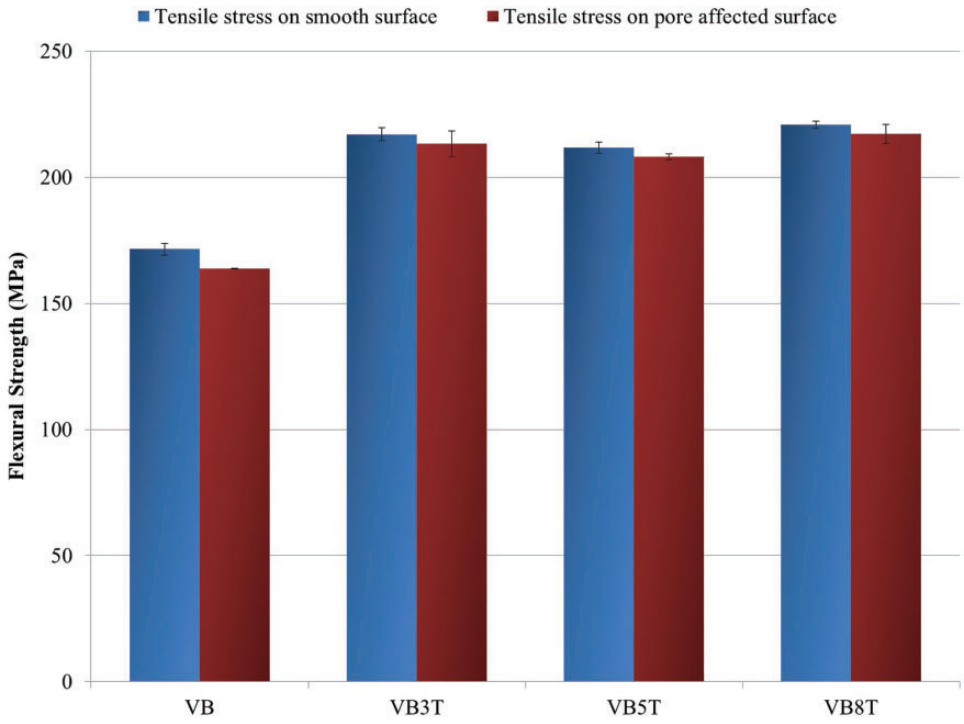

Figure 6. Flexural strength of the composites.

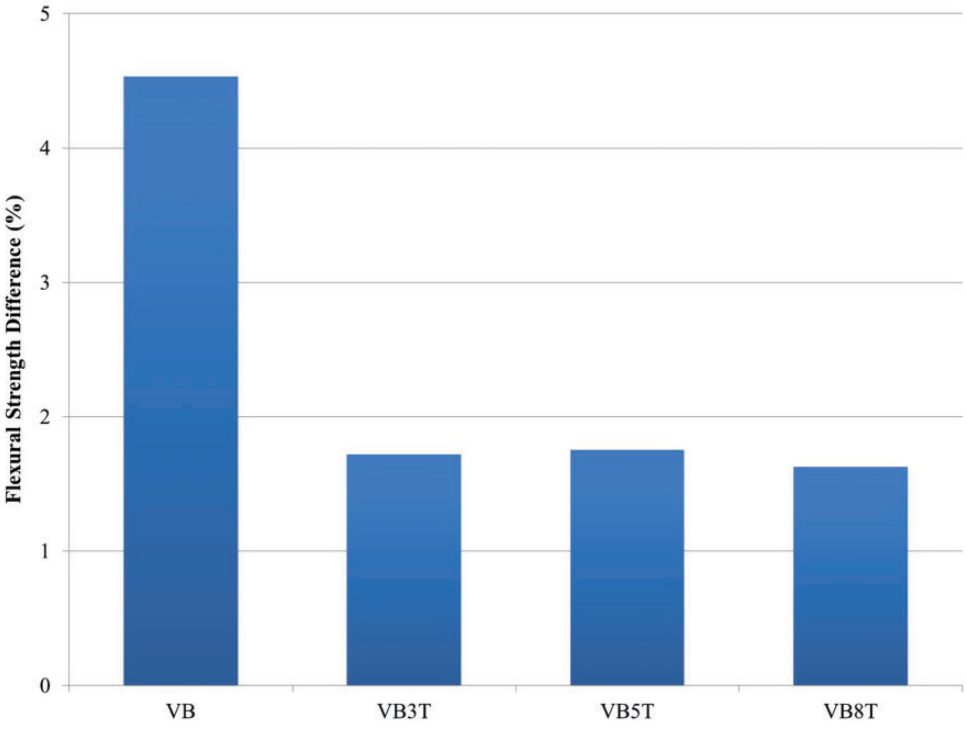

Figure 7. Flexural strength difference observed when the flexural tests were performed with the porous side of the composite under tension and under compression.

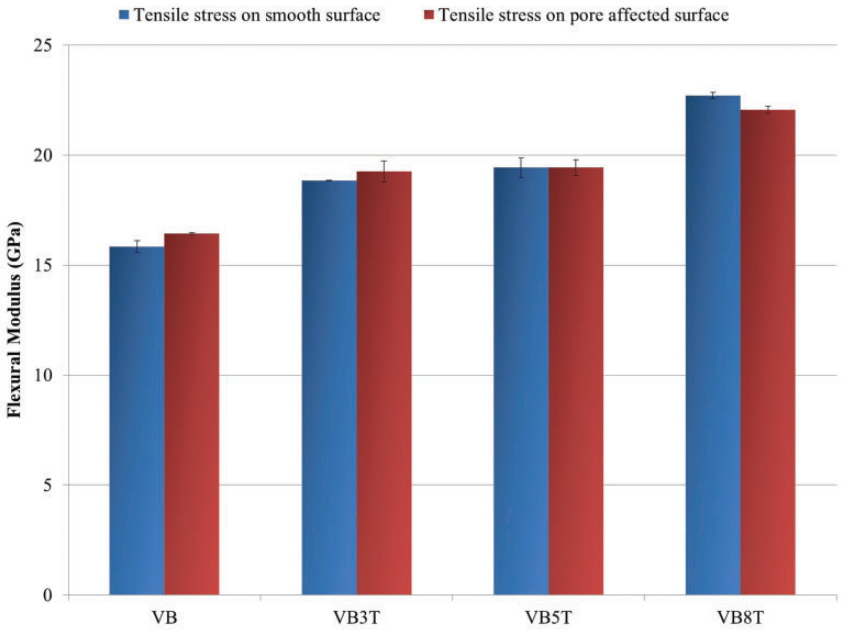

Figure 8. Flexural modulus for all the composites.

strength of both sides of the composite (almost 5% for VB and 2% for the others) is relatively small if compared to the large difference found among these composites regarding the surface porosity (Figure 4), suggesting that the superficial porosity had little effect on the composites' mechanical performance.

The flexural modulus of the composites increased with the external compaction pressure during cure and thus with the fiber volumetric content. VB8T composite showed a flexural modulus 43% higher than the VB composite. In addition, the modulus was not significantly affected by the surface pores. These results are shown in Figure 8.

The effect of the external compaction pressure on the tensile strength and Young's modulus of the composites is shown in Figure 9. A clear tendency can be observed where the tensile properties increased as the compaction pressure during processing did. One of the main reasons for this is the higher fiber volume fraction of these composites. It is well known that the mechanical properties (strength and stiffness) of composites increase as the fiber volumetric fraction does. Usually an upper limit exists over which the mechanical performance starts to decrease as the fiber content increases, due to insufficient fiber wetting by the matrix. However, results showed that this value was not reached in this work at the highest fiber content obtained (56%). Better fiber-to-resin ratio enhances both the strength and the modulus of the composites. The gain in tensile strength of VB8T with respect to the vacuum-bagged composites was around 38%, higher than the improvement observed in the flexural tests. In addition, a significant improvement in Young's modulus was observed as the external compaction was increased. The tensile modulus of VB8T composite was 60% higher than that of the VB composite.

Tensile tests were also carried out on neat resin samples, which showed a strength of 63.9 MPa and a modulus of 3.3 GPa. Under tensile loading of UD composites in the direction of fibers, the rule of mixture suggests that the relationship between the composite strength (and modulus) and the fiber volume fraction is a straight line. This line represents the theoretical upper bound for the property (strength or modulus) that can be obtained in the composite, since all the fibers are oriented in the loading direction. Figure 10 shows the plots "strength vs. fiber content" and "Young's modulus versus fiber content" for the composites under study and the fitting equations for the data points as well. The resin properties were also included as data points for improving the fitting accuracy, but these points are not shown in the plot for better visualization of the composites' behavior. According to the rule of mixtures

$$\sigma_c = \sigma_m + (\sigma_f - \sigma_m) * v_f \quad (2)$$

$$E_c = E_m + (E_f - E_m) * v_f \quad (3)$$

where v_f is the fiber volume fraction; σ_f, σ_m (equal to 63.9 MPa), and σ_c are the tensile strengths of the fibers, matrix, and composite, respectively; and E_f, E_m (equal to 3.3 GPa), and E_c are the Young's modulus of the fibers, matrix, and composite, respectively. Therefore, an estimation for the tensile properties of flax fibers

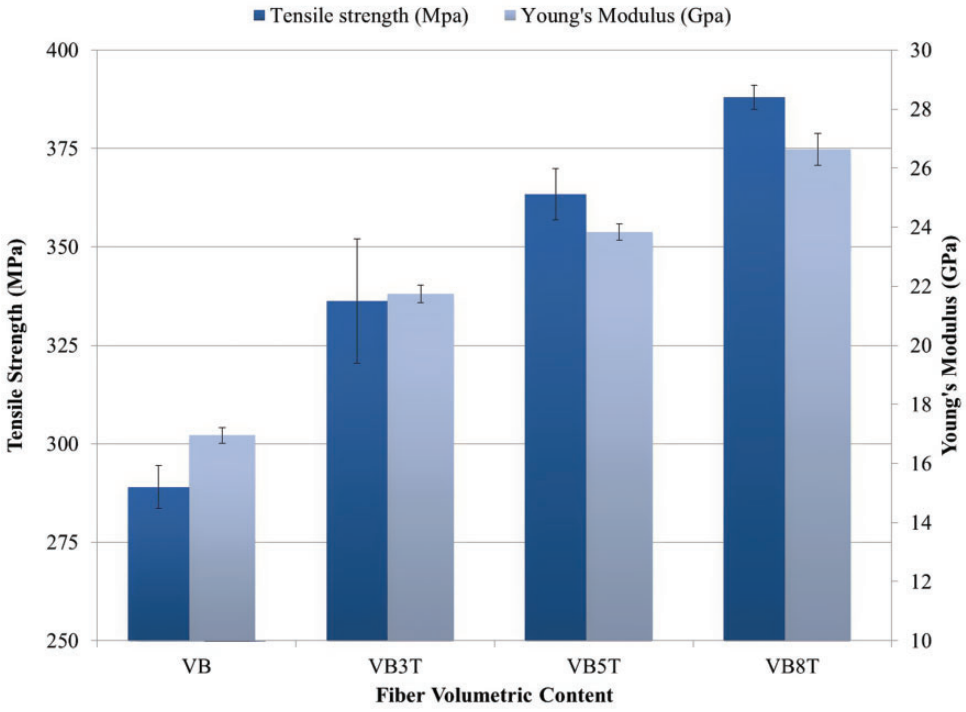

Figure 9. Tensile strength and Young's modulus of the composites.

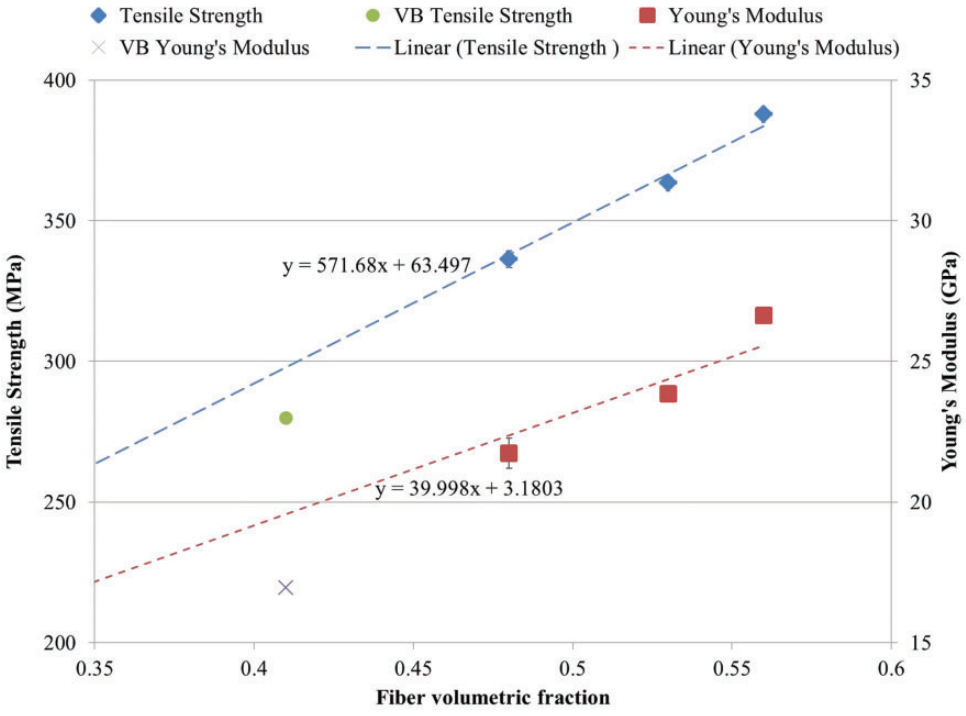

Figure 10. Rule of mixtures for tensile properties.

could be done from the slope of these curves, obtaining a value of 635.2 MPa and 43.2 GPa for the strength and modulus, respectively. These values are quite consistent with those reported by Charlet et al.[30] who measured the tensile properties of flax fibers taken from different location in the plant stem. Their results are summarized in Table 2 where it can also be seen that flax fibers, as all plant fibers, present a very large variability in their

properties, due to the huge variations of diameter along a single fiber and kink bands, which are geometrical singularities that bring about stress concentrations in the fibers.[30] Interestingly, it was found, accordingly with other authors' results (see Table 3), that this large variability is greatly reduced in the composites, probably because of the large number of fibers acting simultaneously during the composite loading.

It should be noted that the data points corresponding to the strength and modulus of the VB composite were not considered for fitting the rule of mixtures. This was done on purpose in order to obtain fitting curves representing the variation of each property with the fiber content for the composites obtained by the manufacturing technique that combined both vacuum bagging and compression molding. Therefore, analyzing the experimental data point of the VB composite in the plot, it was possible to determine if the lower mechanical performance of this material was caused by the lower fiber volume fraction or by other mechanisms, such as premature failure due to superficial porosity or internal voids. It can be seen in Figure 10 that the experimental tensile strength of the VB composite fell below the line representing the rule of mixtures, suggesting that the internal voids found in the microstructural analysis and the superficial porosity (possibly in less extent, as found in the flexural test results) weakened the composite strength. However, the difference between the expected strength given by the rule of mixtures and the strength found experimentally was 6%, suggesting that although the defects present in VB weakened the material, their influence on the final strength is less significant than the influence of changing the fiber volume fraction. Young's modulus of VB was also lower (15%) than the one predicted by the rule of mixtures. These results are consistent to those reported by Varna et al.[3] who found a decrease of the tensile strength and Young's modulus of 5 and 19%, respectively, due to a void content of 4–5% on unidirectional glass fiber/epoxy composites.

Table 3 summarizes some results obtained in literature for the tensile properties of unidirectional flax/epoxy composites. For comparison purposes, the rule of mixtures was used to extrapolate the strength and modulus of the type of composite made in this work by matching the exact fiber content reported by the authors. These values are shown between parentheses in Table 3 where it can be seen that the properties were comparable to those of pultruded unidirectional composites and higher than those obtained by other authors using compression molding.

Figure 11 shows the strain at break for all the composites under tensile tests. The largest strain at break was found for the VB composite, which in fact is the one that has visible internal voids in its microstructure. Varna et al.[3] probed that the presence of voids has a positive effect in this property, explaining that few large and well-defined transverse cracks appear in low void content laminates before final failure, while multiple

Table 2. Flax fiber tensile properties measured by Charlet et al.[30]

Location in stem	Young's modulus (GPa)	Strength (MPa)	Ultimate strain (%)
Top	59.1 (±17.5)	1129 (±390)	1.9 (±0.4)
Middle	68.2 (±35.8)	1454 (±835)	2.3 (±0.6)
Bottom	46.9 (±15.8)	755 (±384)	1.6 (±0.5)

Table 3. Tensile properties of UD flax/epoxy composites.

Ref.	Vf (%)	Manufacturing method	Young's modulus (GPa)	Tensile strength (MPa)
Charlet et al.[30]	20%	Wet impregnation plus compression molding	13.4 ± 2.1 ***(10.6)***	122 ± 14 (***177***)
Gning et al.[31]	42%	Wet impregnation plus compression molding (6 plies, 5.9 bar of pressure)	15.61 ± 0.38 ***(19.4)***	150.0 ± 10.7 ***(303)***
	37.1	Wet impregnation plus compression molding (6 plies, 3.1 bar of pressure)	6.33 ± 0.85 ***(17.4)***	58.3 ± 6.5 ***(275)***
Oksman[32]	32%	Resin transfer molding (RTM)	15.0 ± 0.6 (***15.4***)	132 ± 51.2 ***(246)***
Heijenrath and Peijs[33]	50%	Pultrusion	24 (***22.5***)	325 ***(349)***

UD: Unidirectional.
The value of each property for the type of composites made in this work and extrapolated with the help of law of mixtures is shown between parentheses.

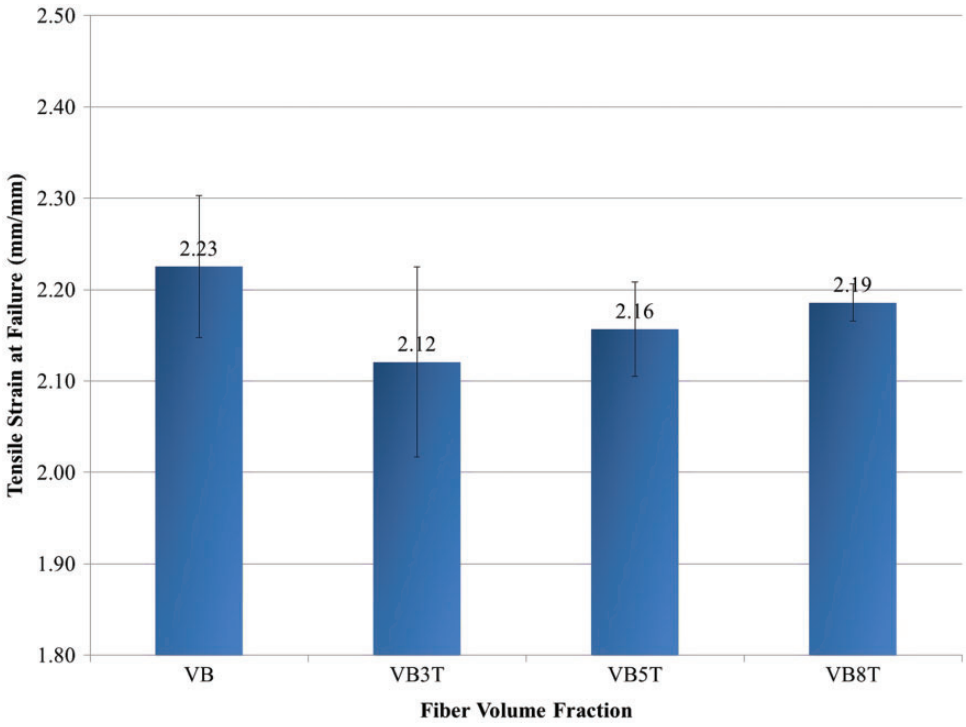

Figure 11. Strain at failure under tensile loading.

transverse cracks with irregular shape as well as numerous smaller cracks are formed in the higher void content laminates. The irregularity of these cracks resulted in lower stress concentration and stress level allowing the material to deform more before failure. However, the difference in the strain at break among all the composites studied in this work is small, thus it seems that the compaction stage after bagging the laminate was effective in providing better strength and modulus while not affecting significantly the strain at failure. Similar results were reported by Charlet et al.[30] who found a tensile failure strain practically independent of the fiber content of unidirectional flax fiber composites.

Conclusions

In this work, unidirectional flax fiber/epoxy composites were manufactured by the vacuum bagging technique only and vacuum bagging followed by a compression molding stage under different compressive loads. The external pressure dramatically improved the surface quality of the composites, decreasing the area of superficial pores from 30% to between 3 and 5% depending on the applied pressure. It was found that this porosity slightly reduced the flexural strength of the composites, but this detriment was not significant if compared to the effect of changing the fiber volume fraction by the different applied pressures. In general, the mechanical performances (flexural and tensile) improved as the external pressure used during the curing of the laminates was higher, which was mainly attributed to the better fiber-to-resin ratio and also to the improved microstructures with less amount of voids obtained when the compression molding stage was performed on the vacuum-bagged laminates. But again, the effect of these defects on the properties was not as significant in comparison to the impact caused by changing the fiber volume fraction. Therefore, the main cause for the properties enhancement seemed to be the improvement in the fiber volumetric content.

Declaration of Conflicting Interests

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