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Original Research

Characterization of pultruded composites of vinyl ester and unsaturated polyester resins with different fiberglass reinforcements

Laura Gallina Moscone[1]
Willian Belincanta Ribeiro[1]
Diego Piazza[1]
Rosmary Nichele Brandalise[1]*
[1] Universidade de Caxias do Sul, Brazil.
* Corresponding author: rnbranda@ucs.br

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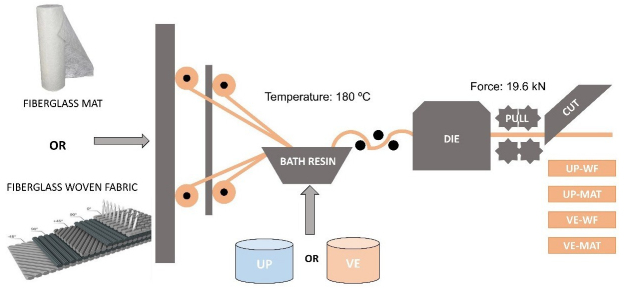

Abstract: Different combinations of matrices and reinforcements in composites make the study of this class of materials a challenge, especially when pultrusion is the manufacturing process employed. Pultrusion is well documented in the literature and offers numerous applications across various sectors, including automotive, construction, aerospace, and furniture industries, among others. In this study, glass fiber-reinforced resin composites were produced via pultrusion, varying between unsaturated polyester (UP) and vinyl ester (VE) resins, and glass fibers in the forms of filaments, woven fabric (WF), and mat (MAT). The composites morphological properties (SEM), physical properties (density and void content), dynamic-mechanical properties (DMA), and mechanical properties (tensile and impact strength) were evaluated. Considering the properties assessed, composites with vinyl ester resin exhibited similar density, higher glass transition temperature, greater storage and loss moduli by DMA, improved matrix/reinforcement adhesion as observed by SEM, higher tensile and impact strengths, and lower void content compared to those with unsaturated polyester resin. Regarding the reinforcement type, the mat presented superior thermal, morphological, and impact resistance properties, whereas the woven fabric demonstrated lower void content and higher tensile strength than the mat. Ultimately, the best results among the produced composites were obtained with the VE/MAT and VE/WF samples.

Keywords: Composites, polyester, vinyl ester, glass fiber, pultrusion.

Introduction

Composites produced by the pultrusion process have great potential for applications across various fields such as civil construction, automotive, furniture, sports, aerospace, biomaterials industries, among others [1]. In addition to this applications, they offer lightweight structure, easy installation, high mechanical and chemical resistance, as well as thermal and acoustic insulation, electromagnetic transparency, and long-term durability in aggressive environments [2, 3].

A composite consists of a polymer matrix, which is the continuous phase, and reinforcement, the discontinuous phase. The matrix can be made from various materials, with unsaturated polyester and vinyl ester resins being among the most commonly used in pultrusion. Typically, reinforcements involve different types of fibers, such as glass and carbon fibers, among others [4]. Moreover, it is possible to apply different reinforcement combinations by varying their form in the process, ranging from filaments, mats, and fabrics with different fiber orientations [5].

The pultrusion manufacturing process is considered a continuous process, maintaining a constant cross-section throughout the length, which provides structural uniformity [6]. Matrix application during the process can occur via resin injection into the die or by using a resin impregnation tank. In resin bath pultrusion, reinforcements are submerged in a resin container and impregnated, then pulled through the die where curing occurs [7]. Proper control of resin viscosity, pulling speed, and die temperature is essential, since these parameters directly influence the formation of voids, degree of impregnation, and final mechanical performance [8, 9].

Unsaturated polyester resin allows the production of composites with notable properties, including low density (between 1.10 and 1.20 $g \cdot cm^{-3}$), high mechanical strength (tensile and flexural strength between 50 and 54 MPa, respectively), elevated thermal stability (thermal conductivity between 0.17 and 0.27 $W \cdot m^{-1} \cdot K^{-1}$), high durability, and ease of

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handling [10]. This resin is widely employed in pultrusion due to its attractive cost-benefit ratio; although its properties are inferior to epoxy resin, it is considerably less expensive [11].

Vinyl ester resin formation requires the reaction between methacrylic acid and epoxy resin., presents an intermediate behavior between epoxy and polyester resins [10]. It combines the ease of processing of polyester resin with the chemical resistance of epoxies, exhibiting stronger bonding, i.e., a more effective matrix/reinforcement interaction. Therefore, it is frequently applied when both mechanical performance and chemical durability are required [12, 13].

One of the most commonly used reinforcements in pultrusion is glass fiber, due to its high tensile strength, which makes its use viable in the process [14]. Glass fibers are based on fused silicas (SiO_2) with oxides and have fiber diameters ranging from 5 to 20 µm [15]. They provide high tensile strength (up to 3450 MPa) and are non-conductive and resistant to humidity and temperature variations [16]. Different fiber architectures — filaments, mats, and woven fabrics — strongly affect resin flow, wetting behavior, and load transfer efficiency, leading to different levels of adhesion and void formation [17–19].

In addition to different reinforcement types used in pultrusion, variations in the form of reinforcement application are possible [18]. A wide variety of fabrics are produced using conventional weaving looms. The weave type influences formability, moldability, and fiber reinforcement efficiency. The weave consists of warp fibers running in the loom direction and weft fibers (fill) perpendicular to the warp. The main fabric reinforcement styles, which can be made from glass or other fibers, are plain, twill, satin, and basket weaves [19].

Composite reinforcement can also receive additives or coupling agents designed to improve fiber–matrix interfacial adhesion, thereby enhancing composite mechanical and thermal performance. Several studies have recently demonstrated that fiber architecture, surface treatment, and resin viscosity jointly affect void content, interfacial bonding, and load transfer efficiency in composites [19–21]. However, comparative investigations involving different resins and reinforcement configurations remain limited [21].

Therefore, the objective of to evaluate the morphological, physical, dynamic-mechanical, and mechanical properties of two resin types, vinyl ester and unsaturated polyester, using filament-mat and filament-fabric glass fiber reinforcements, produced via pultrusion. This work aims to compare the performance of different resin and reinforcement combinations, and to clarify how each combination influences composite behavior and quality. Although pultrusion is widely used in industry, there is still lack of systematic studies simultaneously evaluating the effects of variables such as matrix type (UP and VE) and reinforcement form (mat and woven glass fiber fabric) on the overall composite performance. This gap limits the understanding of how resin–reinforcement interactions jointly influence morphological, thermal, and mechanical performance. Thus, this research contributes to advancing the technical-scientific understanding of the structural behavior of these materials, providing relevant insights for both practical applications and optimized pultruded composite designs.

Experimental Section

Materials

The unsaturated isophthalic polyester resin used was OMEGA 1017 from Embrapol (Brazil), with a viscosity of 2800 – 3300 cP. The vinyl ester resin was DION IMPACT 9100 from Reichhold (United States), with a viscosity of 520–620 cP. The glass fiber was supplied in the form of direct roving SE1200 (specifically designed for pultrusion) with a TEX ($g{\cdot}km^{-1}$) of 4,400 from Owens Corning (United States), as continuous glass fiber mat Unifilo (300 $g{\cdot}m^{-2}$), and as woven glass fabric TDS with 0º and 90º fiber orientation (500 $g{\cdot}m^{-2}$), LT0350, all from Owens Corning, with stitched mat (150 $g{\cdot}m^{-2}$).

The reinforcement system consisted of combinations of filament roving with either mat or fabric to obtain the different composite configurations analyzed in this study. The total reinforcement content in the composites was approximately 55 wt%. Additionally, fixed amounts of zinc stearate (AMC do Brasil), alumina (Alcoa), calcium carbonate (Topsul), styrene monomer (Brisco), and non-reactive white pigmented paste (Morquímica) were used in the composite formulation. These components remained constant throughout all formulations to ensure consistency in the comparative analysis.

Composites manufacturing

The composites were developed via pultrusion in partnership with Pultrusão do Brazil (Passo de Torres, SC, Brazil), using a pultrusion machine composed of three zones: the alignment and impregnation zone, where the reinforcement is aligned and passed through a resin impregnation tank; the die heating zone, maintained at 180 ºC, where the resin cures along with the reinforcement inside the die geometry; and the pulling zone, which initially applies a force of 19.6 kN and later reduces to 14.7 kN. These processing parameters were kept constant for composite production, with the only difference being the pulling speed: 0.381 $m{\cdot}min^{-1}$ for the unsaturated polyester resin and 0.304 $m{\cdot}min^{-1}$ for the vinyl ester resin. The pultrusion temperature profile, pulling speed, and curing time were selected based on preliminary trials to ensure full impregnation and complete resin polymerization, avoiding voids and delamination.

The coding used for the composites in this study was: unsaturated polyester resin + glass fiber filaments and mat (UP/MAT), unsaturated polyester resin + glass fiber filaments and woven fabric (UP/WF), vinyl ester resin + glass fiber filaments and mat (VE/MAT), and vinyl ester resin + glass fiber filaments and woven fabric (VE/WF). In addition to this coding, composite properties were evaluated in two orientations: the X-direction, corresponding to the direction in which the filaments pass through the resin bath and are pulled into the die, and the Y-direction, transverse to the filaments.

The comparison between mat and woven fabric as reinforcement forms is justified by their distinct structural characteristics, which directly influence resin distribution, matrix/reinforcement adhesion, and mechanical performance. The mat, composed of randomly oriented fibers, tends to absorb impacts and distribute stresses more diffusely, whereas the fabric, with a controlled 0°/90° fiber orientation, promotes greater fiber alignment with the load direction, thereby increasing tensile strength. Evaluating these two configurations allows understanding of how reinforcement architecture affects the overall composite performance. All manufactured profiles were visually inspected for uniform surface finish, absence of cracks, and dimensional stability before being cut into specimens for testing.

Characterization of the composites

The composites were characterized in terms of their morphological, physical, dynamic-mechanical, and mechanical properties.

The morphology of the composites was evaluated after manual fracture as well as after mechanical polishing of the cross-section, followed by gold deposition. Subsequently, the samples were analyzed using a MIRA3 scanning electron microscope (Czech Republic) at magnifications ranging from 500× to 5000×, operating at 12 kV.

Composite density was determined according to ASTM D792-13 Method A, which employs water as the immersion liquid. Five specimens were analyzed for each composite condition.

The void content of the samples was determined following ASTM D2734-16, using Equation 1 to calculate the theoretical composite density, and Equation 2 to obtain the void content (V).

$$T_d = 100 * (R/D + r/d) \quad (1)$$

$$V = \frac{100 * (T_d - M_d)}{T_d} \quad (2)$$

Where Td is the theoretical composite density, R is the resin content in wt%, D is the resin density, r is the reinforcement content in wt%, d is the reinforcement density, and Md is the actual density. For the reinforcement density, the density of glass fiber was considered as 2.55 g·cm^{-3} [20], and for the resin, a calculation was performed including the additives used, resulting in specific densities for each formulation.

Dynamic mechanical analysis (DMA) of the composites were performed using the dual cantilever method on a DMA Q800 apparatus (United States), with rectangular specimens measuring 10 mm × 60 mm. The test parameters were a strain amplitude of 0.1%, frequency of 1 Hz, heating rate of 3 ºC·min^{-1} and a temperature range from 25 ºC to 200 ºC. Using the storage modulus values obtained for each sample in the glassy region (E'_g) and in the rubbery region (E'_r) the reinforcement effectiveness coefficient (C), was calculated according to Equation 3. Additionally, using the tan δ values for the composite and the resins, along with the reinforcement volume, the adhesion factor (A) was calculated following Equation 4.

$$C = \frac{E'_g/E'_r\ (composite)}{E'_g/E'_r\ (resin)} \quad (3)$$

$$A = \frac{1}{1 - \phi f}\frac{\tan\delta\ (composite)}{\tan\delta\ (resin)} - 1 \quad (4)$$

The reinforcement effectiveness coefficient C is calculated using the storage modulus in the glassy region (E'_g at 40 ºC) and in the rubbery region (E'_r at 150 ºC). To calculate the adhesion factor A, the loss factor (tan δ) of the composite and the resin at the glass transition temperature, as well as the reinforcement volume fraction (ϕf), were used.

Since obtaining pure resins sample was not possible due to the presence of other components, the required reference data were adopted from the DMA tests reported by Romanzini et al. (2012) [21] for the unsaturated isophthalic polyester resin and by Wirti et al. (2019) [22] for the vinyl ester resin, based on the DMA curves presented in those studies. The values of E'_g, E'_g and tan δ were 4000 MPa, 18 MPa, and 0.58, respectively, for the unsaturated polyester resin, and 2161 MPa, 15 MPa, and 1.05, respectively, for the vinyl ester resin [21, 22].

Tensile strength tests of the composites were conducted according to ASTM D638-14, Type I, using specimens measuring 165 × 19 mm, on a universal testing machine model DL 20000 from EMIC (Brazil). The tests were performed with a 19.6 kN load cell, a crosshead speed of 5 mm·min^{-1}, and a gauge length of 300 mm, with five specimens per condition.

Impact resistance analysis was carried out in accordance with ASTM D256-06, using the notched Izod method (45º notch). A pendulum delivering 7.5 J of energy was used to strike vertically positioned specimens. Ten specimens were tested for each formulation to ensure statistical consistency.

Results and Discussion

The morphology of the composites was evaluated by SEM (Figure 1), allowing observation of the interaction between the matrix and the reinforcements. The dark areas observed in the micrographs correspond to the resins, varying between polyester and vinyl ester, while the lighter areas correspond to the glass fiber reinforcement.

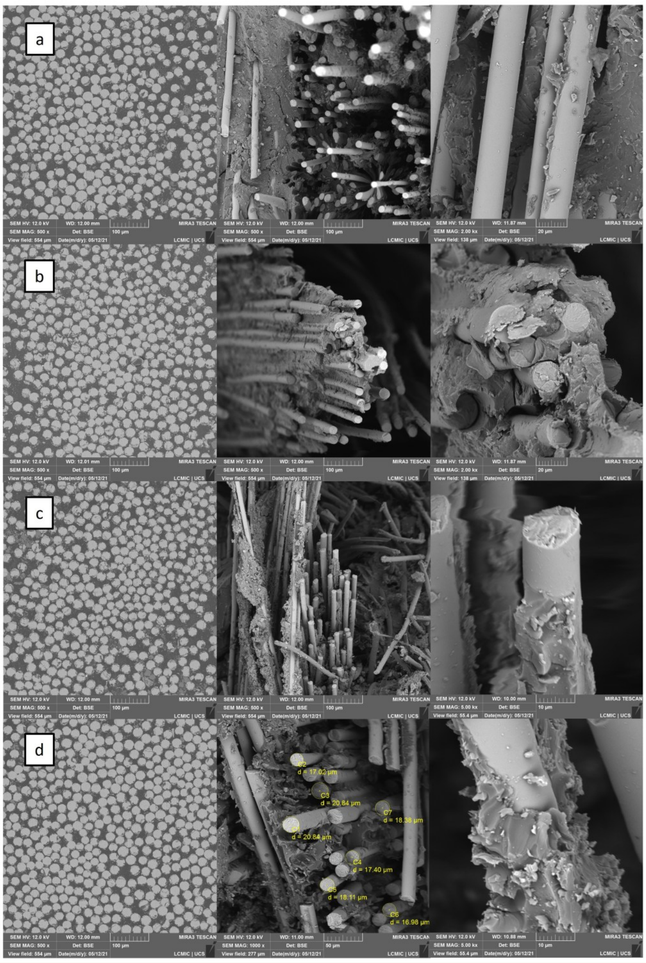

Figure 1. SEM micrograph of samples (a) UP/WF, (b) UP/MAT, (c) VE/WF and (d) VE/MAT produced by pultrusion, the first of the polished surface and the other two of the manual fracture (magnifications in 500, 1000, 2000, 5000x).

Table 1 presents the observations made from the micrographs, aiming to assist in the evaluation by defining certain characteristics:

- For reinforcement distribution, the categories assigned were: uniformly distributed, regular, and agglomerated.
- For matrix/reinforcement interaction, the classifications used were: weak, moderate, and good.
- For voids in the matrix, the descriptors were: more evident, adequate for the process, and less evident.

The micrographs revealed regions containing some voids with resin absence and filament agglomerates, regardless of the resin used. This can be explained by the viscosity values associated with the resins, which range from 2800 to 3300 cP for the unsaturated polyester and from 520 to 620 cP for the vinyl ester [20]. High viscosity hinders complete wetting of the reinforcement, promoting voids and reinforcement agglomeration.

Composites with vinyl ester resin demonstrated better reinforcement distribution and matrix/reinforcement interaction, consistent with the lower viscosity of this resin, which improves fiber wetting and reduces void formation. Similar findings were reported by Ravikumar et al [23], who observed that lower-viscosity vinyl ester systems enhance impregnation and adhesion in pultruded glass fiber composites.

Regarding the reinforcement type, samples containing mat exhibited better matrix/reinforcement interaction and more uniform reinforcement distribution within the matrix compared to fabric-reinforced samples. These results agree with Karnoub et al. [24], who reported that random fiber orientation in mat reinforcements promotes a more homogeneous stress distribution and improved interfacial adhesion.

Among the samples analyzed, the one showing superior performance according to the findings in Table 1 was VE/MAT, which exhibited better homogeneity between matrix and reinforcement, greater filling of void spaces, and absence of defects, confirming more efficient matrix/reinforcement adhesion. This suggests that both resin viscosity and reinforcement architecture play a synergistic role in determining interfacial quality and microstructural integrity.

Table 1. Evaluation of micrographs obtained by SEM for UP/WF, UP/MAT, VE/WF and VE/MAT considering the morphologies cited in the literature on the subject.

Sample	Resin/fiber interaction	Reinforcement distribution in the matrix	Void content in the matrix	Support sources consulted
UP/WF	Moderate	Between regular and uniformly distributed	Suitable for the process	Sugiman et al. (2019)[25]
UP/MAT	Moderate	Between regular and uniformly distributed	Suitable for the process	Vieira *et al.* (2020)[20]
VE/WF	Good	Between regular and uniformly distributed	Suitable for the process	Pun e Singh (2019)[26]
VE/MAT	Good	Uniformly distributed	Suitable for the process	Vieira *et al.* (2020)[20]

Note: Matrix–fiber interaction – weak, moderate, and good matrix–fiber interaction. Reinforcement distribution in the matrix – uniformly distributed, regular, and agglomerated. Voids in the matrix – more evident, adequate, and less evident.

The densities of the composites with unsaturated polyester resin and vinyl ester resin, varying the type/combination of reinforcement as mat or fabric, are shown in Figure 2. The obtained values were similar, confirming that the composite composition, variation in resin and reinforcement types does not significantly affect the density. This occurs because the total reinforcement content remained approximately 55 wt%, and the densities of both resins are close (1.18 g·cm^{-3} for unsaturated polyester and 1.05 g·cm^{-3} for vinyl ester) [22, 27]. Hence, density values are mainly governed by the type and proportion of glass reinforcement rather than the resin matrix itself When compared with similar composites reported in the literature, the values are also close, as shown in Figure 2 [27, 28].

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The results obtained using Equations 1 and 2 for theoretical density and void content are presented in Table 2.

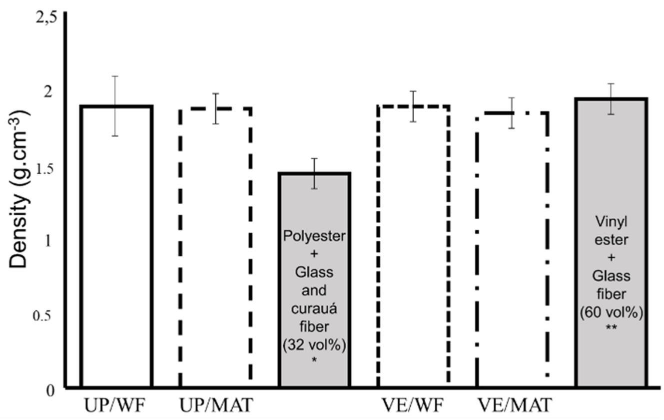

Figure 2. Density of UP/WF, UP/MAT, VE/WF e VE/MAT composites obtained by pultrusion.

Table 2. Void content, theoretical density and real density.

Sample	Reinforcement (wt%)	Reinforcement ($g \cdot cm^{-3}$)	Resin+additives (wt%)	Resin+additives ($g \cdot cm^{-3}$)	Theoretical density ($g \cdot cm^{-3}$)	Void content (%)
UP/WF	54.40	2.55	45.60	1.52	1.95	3.49
UP/MAT	56.40	2.55	43.60	1.53	1.98	5.35
VE/WF	54.40	2.55	45.60	1.46	1.90	1.18
VE/MAT	56.40	2.55	43.60	1.42	1.89	2.81

According to these results, when comparing reinforcement types while keeping the resin constant it was observed that the mat-reinforced composites exhibited a higher void content than those reinforced with fabric. While the mat consists of randomly oriented continuous filaments without a defined pattern. the fabric has an ordered (0°/90°) arrangement. This random distribution may hinder resin penetration in certain areas, leading to localized voids and incomplete impregnation, as also reported by Karnoub et al. [24] with polyester resin composites reinforced with glass fiber fabric and mat produced by compression molding.

Composites with polyester resin showed higher void fraction values compared to those with vinyl ester resin. In the composites studied, both mats and fabrics were located on the surfaces. with filaments forming the core of the. The higher void content in polyester-based composites can be attributed to the higher viscosity of the unsaturated polyester resin (2800–3300 cP), which reduces impregnation efficiency and increases the likelihood of trapped air during the process. Given that fabric layers are positioned on the sheet surfaces, resin can flow more easily toward the core of the composite, whereas mat reinforcements create a more tortuous flow path, making it difficult for the resin to reach the central filaments.

In contrast, composites with vinyl ester resin, due to the lower viscosity of the resin (520 to 620 cP), which facilitates flow and wetting of the reinforcement, resulting in the more homogeneous morphology observed in the SEM analysis. These results were superior for the vinyl ester resin, as confirmed by the lower void content in Table 2.

The storage modulus. loss modulus, and tan delta results obtained from dynamic mechanical analysis (DMA) are presented in Figure 3.

Evaluating the resins, the vinyl ester resin exhibited approximately 12% higher maximum storage modulus values compared to the unsaturated polyester (Figure 3a). This improvement is attributed to the enhanced matrix–reinforcement interaction observed in the SEM analysis (Figure 1) and to the reduced polymer-chain mobility of the vinyl ester resin, which increases stiffness and energy-storage capacity.

Keeping the resin constant, the mat reinforcement showed the best storage modulus performance, with an average increase of 10% compared to fabric-reinforced samples across both resins. This behavior confirms that the random fiber orientation in mats contributes to better stress transfer within the composite.

The glass transition temperature (T_g), read from the peak of tan delta (Figure 3b), was 77 ºC for the UP/WF sample and 84 ºC for UP/MAT. For the VE/WF composite, T_g was 91 ºC, and for VE/MAT it was 96 ºC. For the pure resins, T_g values are 115 ºC for the polyester resin [21] and 113 ºC for the vinyl ester resin [22]. It was observed that T_g increased with improved matrix–reinforcement interaction, as confirmed by SEM, and with increased molecular rigidity. Samples containing vinyl ester resin displayed higher T_g values, consistent with their greater stiffness (Figure 3a). For both matrices, the mat reinforcement resulted in higher T_g values than the fabric reinforcement, indicating more restricted molecular motion and better fiber–matrix coupling.

Another aspect considered in DMA is the breadth of the tan delta curve: the narrower the curve, the better the matrix/reinforcement adhesion [21]. The VE/MAT composite showed the highest T_g and the narrowest tan delta curve. confirming the superior interfacial bonding already evidenced by SEM and the mechanical results. This trend agrees with the observations of Mohanraj et al. [29], who reported that improved adhesion reduces the damping region width in polyester–glass composites.

The loss modulus (E”) represents the material’s ability to dissipate energy, which is related to chain mobility. Therefore, a higher loss modulus is expected in materials with more effective stress transfer between matrix and fibers. Comparing the resins. the vinyl ester systems presented higher E” values. Regarding reinforcement types, the mat configuration yielded superior results suggesting better mechanical coupling and enhanced interfacial friction between fiber and resin.

Figure 3c presents the values obtained from the DMA curves, as well as those calculated using Equations 3 and 4, in addition to data for the pure polyester and vinyl ester resins.

The reinforcement effectiveness coefficient (C) is defined as the ratio between the storage moduli obtained in different regions of the DMA curve (glassy and rubbery). Lower C values indicate higher reinforcement efficiency in restricting polymer-chain mobility, which directly correlates with composite stiffness and load-bearing capacity.

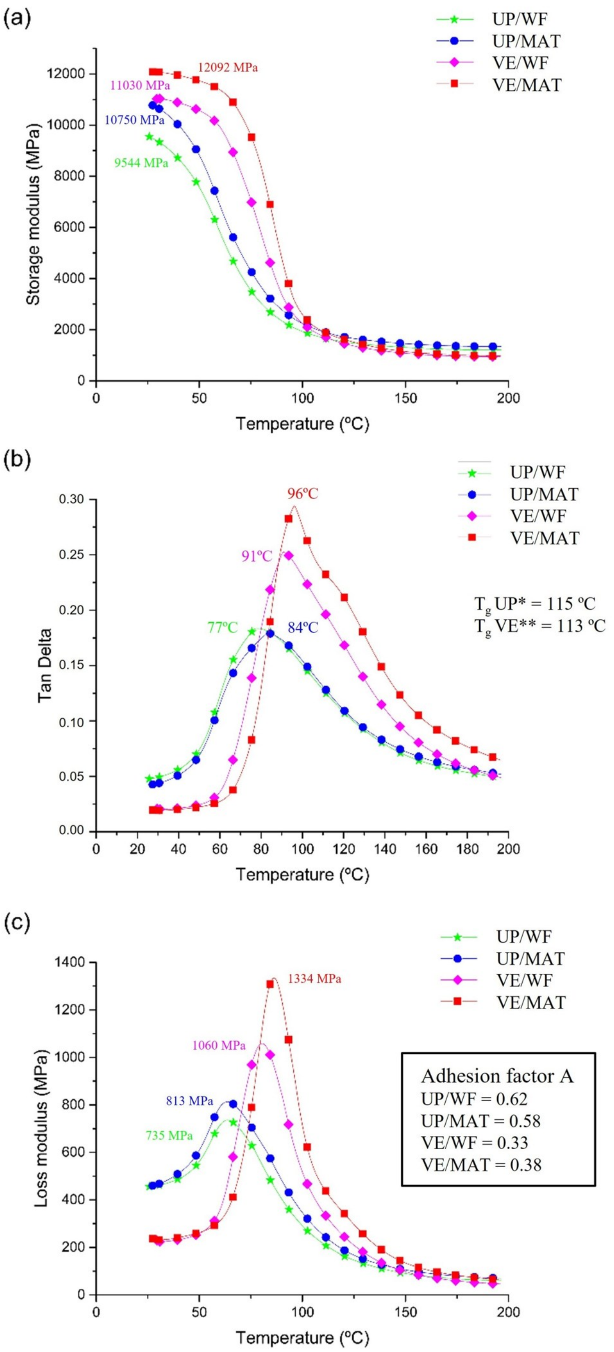

Figure 3. Storage modulus (a). tan delta (b) and loss modulus (c) curves by temperature for the samples UP/WF, UP/MAT, VE/WF and VE/MAT.

Among the composites with unsaturated polyester resin. the best performance was observed for UP/WF, while for the vinyl ester resin, VE/WF exhibited superior results. Thus, fabric reinforcement, due to its ordered weave pattern (0º/90º), ensured greater effectiveness as reinforcement, making it more efficient against external loads.

The adhesion factor (A) is a parameter derived from dynamic mechanical properties (tan δ), indicating the degree of interaction between the matrix and the reinforcement. Lower values of A suggest more efficient stress transfer between the constituents, implying more stronger interfacial adhesion, which consequently enhances mechanical performance and reduces damping capacity.

For the adhesion factor (A) values, among the composites with unsaturated polyester resin, the sample with the lowest value was UP/MAT, indicating more efficient matrix–reinforcement adhesion. In the case of vinyl ester composites, VE/MAT showed the best performance, reinforcing the superior compatibility between vinyl ester resin and glass fiber surfaces, as already evidenced in the SEM and DMA analyses.

The tensile strength and impact resistance results of the samples are presented in Table 3. For the tensile strength tests, the specimen preparation considered the X direction as the direction of filament entry into the die and the Y-direction as the transverse direction to filament orientation.

Regarding the type of reinforcement used, while keeping the resin constant, the mat configuration exhibited the lowest adhesion factor values for both resins, indicating superior fiber –matrix bonding. This behavior is attributed to the random orientation of continuous fibers in the mat, which allows better resin penetration, and more uniform wetting throughout the reinforcement. In contrast, fabric reinforcement with fibers oriented at 0° and 90 present more compact and ordered architectures, which can hinder resin flow and wetting, thereby slightly reducing adhesion efficiency. These findings are consistent with the higher storage modulus and T_g values observed for mat-reinforced composites in DMA (Figure 3), confirming the direct relationship between improved interfacial bonding and overall mechanical performance.

Table 3. Tensile strength in X and Y directions and impact strength of samples UP/WF, UP/MAT, VE/WF and VE/MAT.

Sample	Test specimen orientation	Tensile strength (MPa)	Deformation (%)	Tensile modulus (MPa)	Impact strength ($kJ·m^{-2}$)
UP/WF	Warp X	311 ± 25	13.0 ± 1.1	3174 ± 65	151 ± 12
	Weft Y	87 ± 6	7.0 ± 0.6	742 ± 59	-
UP/MAT	Warp X	280 ± 30	13.0 ± 0.1	3479 ± 10	145 ± 5
	Weft Y	31 ± 3	4.0 ± 0.3	1498 ± 12	-
VE/WF	Warp X	378 ± 36	14.0 ± 1.3	3555 ± 57	157 ± 12
	Weft Y	104 ± 12	7.0 ± 0.6	1024 ± 11	-
VE/MAT	Warp X	358 ± 37	14.0 ± 0.5	3640 ± 18	187 ± 17
	Weft Y	33 ± 3	3.0 ± 0.3	2050 ± 25	-

Note: (X) direction of the filaments and access to the mold; (Y) opposite direction to the filaments.

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The composites produced with vinyl ester resin exhibited superior tensile strength compared to those manufactured with unsaturated polyester resin. This behavior is consistent the SEM micrographs (Figure 1), which showed improved matrix–reinforcement, adhesion and with the higher molecular rigidity of the vinyl ester system as previously discussed in the DMA section.

When comparing reinforcement types while keeping the resin constant the woven fabric composites presents higher tensile strength values than the mat. composites while the elongation at break and elastic modulus remained similar within the experimental deviation. These results are consistent with the findings Karnoub et al [24] who reported approximately 38.5% higher tensile strength for polyester resin composites reinforced with woven glass fabric than for those reinforced with glass fiber mat. The lower void content observed in fabric-reinforced composites (Table 2) also contributes to their greater efficiency in stress transfer and overall tensile performance.

The tensile modulus and strength were higher for specimens tested in the X-direction corresponding to the direction of filament entry into the die. This anisotropy is primarily attributed to the fiber alignment along the pultrusion direction, which enhances load bearing along the axis of reinforcement. This behavior was consistently observed for all samples and was also reported by Besednjak [30], who identified superior tensile properties in the pultrusion X-direction for similar composites.

Regarding impact resistance the samples UP/WF, UP/MAT, and VE/WF exhibited statistically similar results, considering the standard deviations. However, the VE/MAT composite showed distinctly higher impact energy absorption. Although the overall relationship between impact strength and void content was not linear, mat-reinforced composites tended to dissipate more energy, a behavior attributed to their random fiber orientation, which favors microcrack deflection and energy absorption mechanisms.

Similarly, Karnoub et al. [24], observed that polyester resin composites reinforced with mat exhibited up to 15 % higher impact strength than those with fabric, due to greater void-induced energy dissipation.

As discussed previously, the interplay between resin viscosity and reinforcement architecture (layer arrangement and central filament content) directly influences the void formation and, consequently, the impact response, making these correlations complex.

Another relevant aspect worth highlighting is the adhesion factor “A” from DMA, which indicates that the lower the damping capacity of the composite, the higher its mechanical efficiency. It was observed that vinyl ester composites showed the lowest “A” values (0.33 for VE/WF and 0.34 for VE/MAT) and correspondingly the best impact resistance results. This confirms that the enhanced interfacial bonding in vinyl ester systems translates into superior energy absorption and overall mechanical performance.

Conclusions

This study aimed to develop and evaluate pultruded composites materials by varying both the resin system unsaturated polyester and vinyl ester and the type of reinforcement, namely mat with filaments and woven fabric with filaments. Regarding the resin type, it was concluded that vinyl ester resin exhibited superior morphological, physical, thermal, and mechanical properties compared to the unsaturated polyester resin. As for the reinforcement type, the mat configuration demonstrated better morphological, thermal, and impact resistance performance whereas the woven fabric with filaments showed higher values for physical properties and tensile strength.

Among all the studied systems, the composite VE/WF showed the best overall performance in terms of density and tensile strength, while VE/MAT presented superior morphological integrity, impact resistance, and thermal stability. Therefore, it can be concluded that the performance of pultruded composites depends on several interrelated parameters, including resin chemistry, viscosity, reinforcement architecture, and fiber weight fraction. The pultrusion process itself, constant processing conditions, leads to distinct behaviors depending on the flow direction (X and Y directions), primarily due to fiber orientation and resin flow patterns. These findings reinforce that the optimization of pultruded composite materials remains a multidisciplinary challenge, requiring careful balancing of resin properties and reinforcement structures. The results of this study contribute to the understanding of the complex relationships between processing, structure, and performance, supporting the development of advanced composites for structural and industrial applications.

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Authors Contribution

L. G. Moscone: Formal analysis, Investigation, Methodology, Visualization, Writing – original draft; W. B. Ribeiro: Writing - review & editing; D. Piazza: Writing - review & editing; R. N. Brandalise: Formal analysis, Investigation, Project administration, Resources, Supervision, Writing - review & editing. All authors have approved the final version of the manuscript.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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