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Physical and mechanical properties of laminar composites depending on the production methods: an experimental investigation

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Abstract. In this study, the effects of different manufacturing methods on the physical and mechanical properties of carbon/epoxy composite laminates were investigated. The hand lay-up, compression moulding, and vacuum bagging methods with two different vacuum characteristics were selected as the applied methods. The fibre volume fraction (V_f), density, and void content of the composites were measured. The results showed that different manufacturing methods yielded different V_f results. As the V_f values increase, the composite density increases, and the void content within the laminates decreases. Also, the actual and the theoretical density values get closer with increasing V_f values. The tensile and flexural properties of the laminated composites were obtained with mechanical testing as per the ASTM standards. The higher the V_f value, the higher mechanical properties were obtained. The reduced void content within the composite structure could be attributed to better wet out of fibres with the matrix; hence, improved fibre-matrix interfacial bonding was obtained. The higher mechanical properties were achieved due to better load transfer between the fibre and matrix. A single objective optimization was conducted with ANOVA, and empirical equations were derived. The empirical equations can now be used to quickly estimate laminate density, strength, and the modulus of the composites depending upon the V_f, which is directly related to the manufacturing technique. The results help the manufacturers to decide the selection of suitable manufacturing methods.

Keywords. Composite manufacturing; fiber volume fraction; void; laminate density; mechanical properties; optimization.

1. Introduction

As the fibre-reinforced polymer composites provide many attractive features such as high strength and stiffness, lightweight, efficient energy savings, better impact characteristics, and chemical inertness, their use is gradually spreading in the fields of aerospace, defence, automotive, marine applications, wind turbine, sports equipment, electrical devices, etc. [1, 2]. Undoubtfully, obtaining the enhanced material properties and the high quality of the composite products are highly dependent on the manufacturing methods. Composite manufacturing methods are typically divided into two main categories: open and closed moulding techniques. In open mouldings, such as hand lay-up and filament winding, the composite laminate is formed on a mould surface, and its top surface is exposed to the atmosphere. These techniques are low-cost, simple, and easy to apply but generally result in a rough surface finish and poor dimensional stability; thus, they depend on labour skills. On the other hand, the closed moulding technique is applied for the laminate, where it is placed between the top and bottom sides of the mould parts or inside a vacuum bag. Resin transfer moulding, compression moulding, pultrusion, autoclave, vacuum bagging, vacuum-assisted resin transfer moulding (VARTM), and resin infusion are common examples of closed moulding [3, 4]. In the literature, the researchers have concentrated on comparing the manufacturing methods considering the product quality in terms of void content within the laminate, fibre volume fraction value, the obtained mechanical properties, and the dimensional accuracy of the product shapes [5–9]. Durgun *et al* [10] applied the hand lay-up (HL), the resin infusion (RI), and the vacuum bag (VB) techniques to compare the tensile and the flexural characteristics of the carbon/epoxy and glass/epoxy composites. The increase in strength values was reported in the order of hand lay-up, vacuum bag, and resin infusion methods. Park *et al* [11] compared the VB method and autoclave process and indicated that the VB process caused approximately 50% higher void content than the autoclave despite its cost-effectiveness. However,

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high investment cost, process complexity, and longer duration, part constraints, lower energy efficiency were stated as the drawbacks of the autoclave process. It was recently reported that studies on the effects of manufacturing techniques on mechanical properties have still been very limited. Choudhary *et al* [12] compared the vacuum-assisted resin transfer moulding (VARTM) and HL methods in terms of the glass fibre-reinforced polymer composites' mechanical properties. The tensile, flexural, and inter-laminar shear strength values were higher for the composites manufactured with VARTM. Because the VARTM process provided higher density for the composite laminate due to the presence of vacuum pressure. Similarly, Kim *et al* [13] compared the resin infusion and HL methods and showed that vacuum pressure contributed to the resin movement inside the composite laminate. Thus, it ensures better mechanical properties. The previous studies showed that the drawbacks of the open moulding methods could be eliminated by applying close moulding techniques. However, each method has inherited features and includes several processing parameters [14, 15]. Some researchers have concentrated on the effect of vacuum pressure on the void content [14, 16, 17]. Yalcinkaya *et al* [18] applied external pressure to minimize the void content to obtain high-quality laminar composites. The external pressure also provides the removal of the excessive resin. The reduced void content and efficient collection of the excessive resin enhanced the compaction of the composite laminate. Some other researchers have put effort into investigating the process parameters of a particular manufacturing method. Zhang *et al* [15] manufactured carbon/epoxy laminates by applying a vacuum-assisted resin infusion method with three different curing cycles considering post-curing and preheating effects. While there was a slight change between the fibre volume fraction values, the percent void content was considerably decreased with preheating, which resulted in better interfacial bonding, flexural strength, and modulus. They claimed that process developments for a particular manufacturing method did not significantly affect the fiber volume fraction value. However, some developments such as using different vacuum characteristics and improved resin flow may increase V_f values and decrease void formations; thus, the product quality can be enhanced. Mujahid *et al* [14] investigated the change of void content and mechanical properties (tensile and flexural) depending upon the process parameters arising from the vacuum bagging method, such as cure cycle, bagging technique, and laminate thickness. But their ANOVA examination showed that the effects of the curing cycle and laminate thickness on void content were found statistically insignificant. Developing bagging technique using double vacuum bag considering separate action of degassing and compaction sections decreased the void formation. However, Mujahid *et al* [14] claimed that the laminates with decreased void content resulted in lower tensile and flexural properties because of the reduction in fiber volume fraction. Also, using a double vacuum bag requires additional precautions and increases the cost of the process.

FRP composites' failure has usually occurred due to the imperfections such as the presence of voids, cavities, and flaws. These defects cause discontinuity in load transfer within the fibre-matrix system, which triggers crack propagation, interrupts thermal conductivity, and adversely affects mechanical strength and stiffness [16, 17]. Voids are typically defined as manufacturing defects, and can generally be formed by volatiles, moisture, and entrapped air within the composites during curing, and the loss of vacuum pressure and leakage accelerates their formation [19]. They act as stress raisers in the laminates; therefore, degradation of the physical parameters and the mechanical properties is inevitable depending upon the void content.

When the previous studies were examined, it is well understood that the presence of voids is related to manufacturing methods [13, 20]. However, some conflicting results (e.g. the relationship between the V_f of the composites and the void content) have been reported in the literature. Mehdikhani *et al* [19] also confirmed that the formation and degradation effects of the voids had not been entirely elucidated, yet the investigations have still been conducted, and it is an ongoing research topic. Researches that eliminate this inconsistency are also rare. Therefore, the present study comprehensively investigates interactions of physical parameters such as fibre volume fractions, void content, and density according to various manufacturing methods. Then the effects of V_f on tensile and flexural properties were examined experimentally.

Moreover, ANOVA was applied to carry out the regression analysis. Empirical equations were obtained to predict the mechanical properties and the laminate density depending upon the fibre volume fraction. Lastly, a single objective optimization was conducted to maximize the strength-to-density and modulus-to-density ratio.

2. Experimental study

The study was carried out based on the systematic flowchart given in figure 1. Firstly, the production of fibre-reinforced polymer (FRP) composite laminates was performed according to the various manufacturing techniques. The purpose here is not only to reveal the effects of different manufacturing techniques on the physical and mechanical properties of the composites but also to examine the change of mechanical properties depending upon the obtained physical parameters. With this aim, the following manufacturing techniques were applied;

- Hand lay-up
- Compression moulding
- Vacuum bagging 1 (Low vacuum capacity: $3.06\ m^3.h^{-1}$, final pressure: 0.2 mbar)

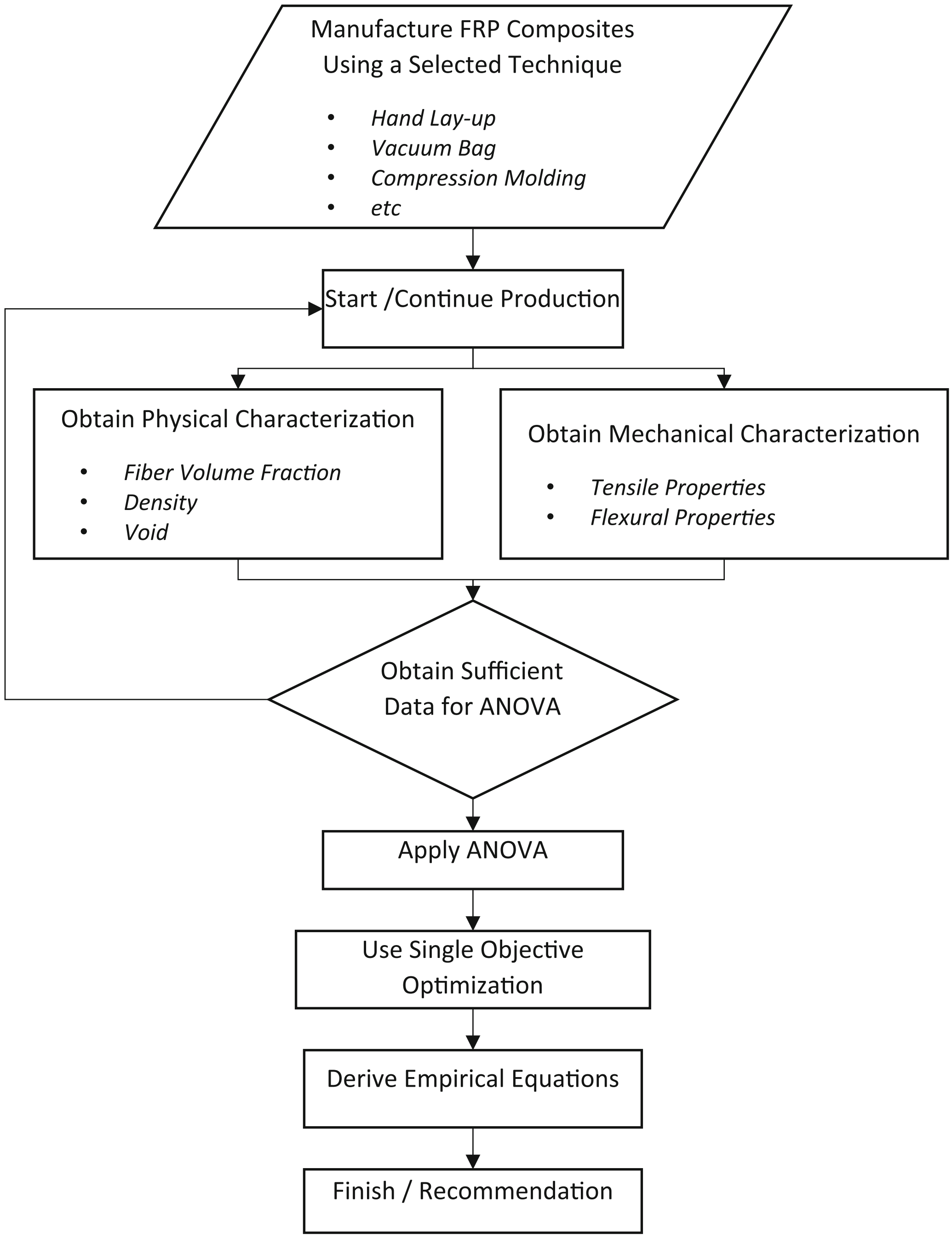


Figure 1. A systematic flowchart of the experimental study.

- Vacuum bagging 2 (High vacuum capacity: 8.5 $m^3.h^{-1}$, final pressure: 0.005 mbar)

After completing the composite laminates' production, the specimens were prepared for physical and mechanical characterization. Fibre volume fraction (V_f) (vol.%), density ($kg.m^3$), and void contents (vol.%) were determined as physical properties, whereas tensile and flexural properties such as strength, modulus, and percent elongation at break were determined as mechanical properties. The interaction of the parameters and the effect of physical parameters on the mechanical properties of the laminated composites were revealed. Then, the effect of V_f on tensile and flexural characteristics was examined using ANOVA. A single objective optimization was conducted, and the empirical equations were derived for the mechanical properties. Lastly, the empirical equations were recommended to researchers and manufacturers to quickly estimate the laminate density, strength, and modulus of the composites depending upon the V_f, which is directly related to the manufacturing technique. The results help them to decide on the selection of suitable manufacturing methods since the methods significantly affect the strength and quality of the final products.

2.1 *Fabrication of composite laminates*

The laminated FRP composites were produced with woven plain carbon fibre fabrics and epoxy resin set as the polymer matrix. The fabrics have 200 g.m^{-2} areal density and 0.2 mm ply thickness. The fibres are continuous and have a density of 1790 kg.m^{-3}, 3800 MPa tensile strength, 1.6% strain, and 240 GPa tensile modulus [21]. Compared to unidirectional fibres, woven plain fabrics provide ease of handling, higher out-of-plane strength, and better dimensional stability in transverse and longitudinal directions since the fill and warp yarns interlace each other [22, 23]. The matrix was prepared with a resin (MGS L160) to hardener (MGS H160) ratio of 100:25 by weight. According to the manufacturer's technical datasheet, it has a density of about 1190 kg.m^{-3}, and its tensile strength, tensile modulus, flexural strength, and strain are approximately 75 MPa, 3.4 GPa, 125 MPa, and 4.5% respectively [24]. This kind of epoxy matrix is more suitable where the bending rigidity and lightweight are essential such as in the applications of aeroplane wings, fuselage and indoors, yacht and shipbuilding, wind turbine blades, and sports equipment.

Three different manufacturing methods, hand lay-up, compression moulding, and vacuum bagging, were applied. Moreover, the vacuum bag method was applied using two different vacuum pumps having different vacuum characteristics. Because the use of higher vacuum pressure results in relatively suppressed void content within the composite laminate, leading to high-quality products [11]. In addition, it was reported in the literature that high vacuum capacity provided better mechanical properties, even the carbon/epoxy laminates produced with the same fibre and matrix characteristics [25, 26]. Therefore, four different types of laminated composites were produced. Figure 2 shows the schematic views of the production methods.

Four plies of woven plain carbon fibre fabrics were used for laminate stacking in all manufacturing methods, so the amount of fibres was kept identical. In the hand lay-up method, the resin-impregnated fibre fabrics were stacked on an open mould, and the laminates were cured under atmospheric pressure at room temperature. In the compression moulding method, the resin-impregnated fibre plies were stacked between the moulds, and the laminates were clamped between the acrylic glass mould parts, then left to the curing process at room temperature. In the vacuum bagging method, the laminates were stacked on an open mould by impregnating each ply with the epoxy resin set, and then a perforated release film and a breather were placed over the laminate, respectively. Lastly, the laminates were enclosed within the vacuum bag, and the curing was carried out at room temperature under a vacuum atmosphere. In all applied manufacturing processes, utmost importance was given during the stacking of each ply to remove the entrapped air within the laminate by using a rolling tool.

2.2 *Determination of fiber volume fraction (V_f)*

The fibre volume fraction (V_f) values of the produced composite laminates were determined with burn-off tests. This determination was also indicated as a successful technique by Abdelal and Donaldson [16]. The tests were performed in a muffle furnace at a temperature of 500°C for one hour according to the procedure provided by ASTM D 3171 – 99 Standard [27]. The weight fractions of fibre and matrix were calculated based on the difference between the initial specimen's mass and fibre mass after the burn-off test. Equation (1) [28] is used to determine the V_f values.

$$V_f = \frac{w_f/\rho_f}{\left(w_f/\rho_f\right) + \left(w_m/\rho_m\right)} \quad (1)$$

where w_f and w_m are the weight fractions of fibre and matrix, respectively. The results obtained in this work are given in table 1. While the hand lay-up method resulted in the lowest V_f value, the highest V_f value was obtained by applying the vacuum bagging method with high vacuum characteristics. The vacuum bagging method with a low-capacity vacuum pump had a minor impact than the hand lay-up method because insufficient vacuum pressure led to resin-rich regions, which generally resulted in high void formation [19]. When comparing the two different vacuum characteristics, it was found that the better the vacuum capacity, the higher V_f values were obtained.

Zang *et al* [15] claim that process developments did not make a significant impact on V_f values. Contrary to the claims of Zang *et al* [15], the present study showed that process development enhanced product quality by increasing the V_f value in the vacuum bagging method. Compression moulding and high-capacity vacuum bagging methods provided improved V_f due to the better compaction pressure. Similarly, Yalcinkaya *et al* [18] confirmed that the external pressure contributed to higher fibre volume fraction values. However, although Choudhary *et al* [12] drew attention to the importance of fibre volume fraction on physical and the mechanical properties of the FRP composites, they did not evaluate the effect of V_f, which is mainly affected by the manufacturing method.

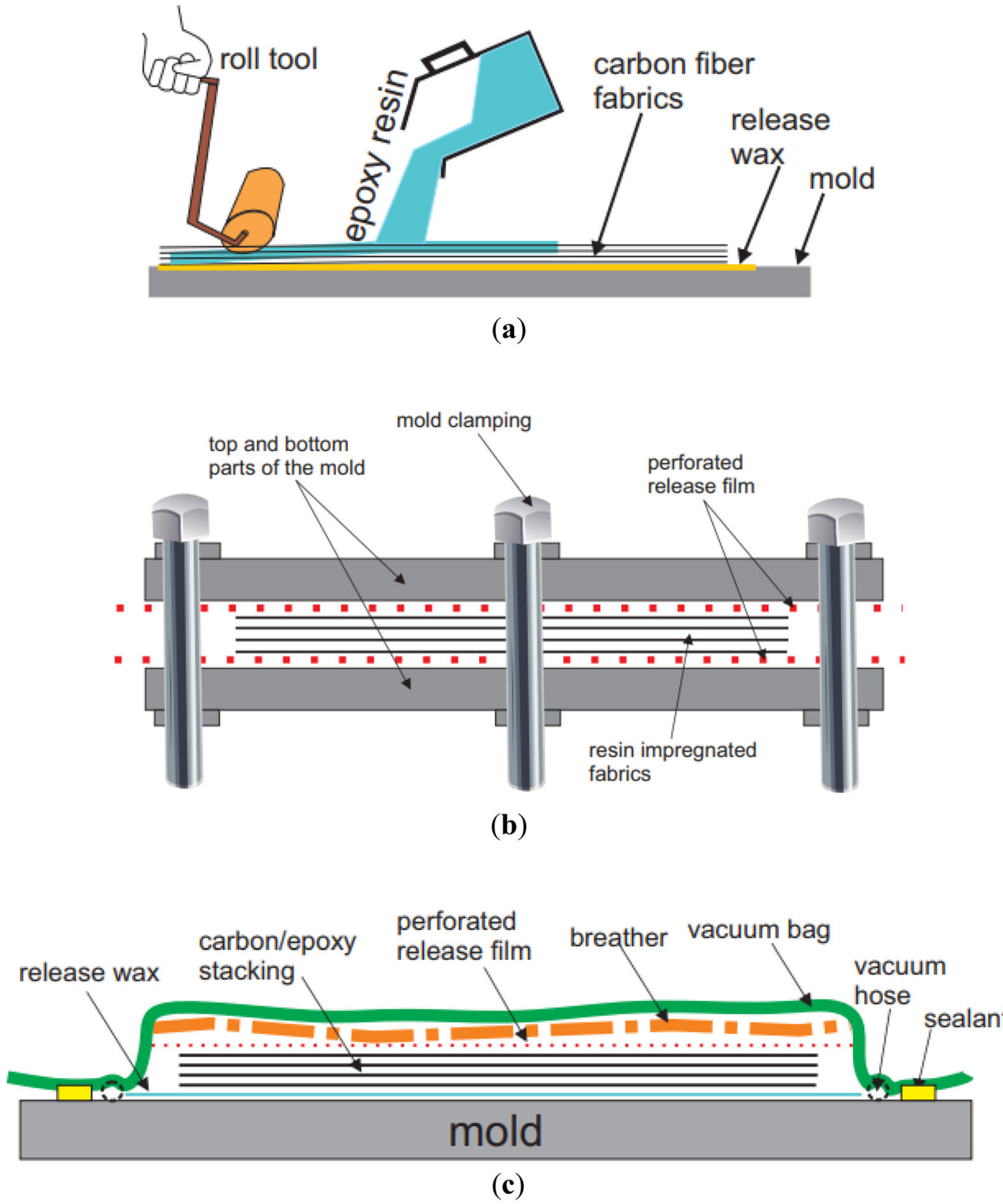


Figure 2. Schematic views of the production methods; (**a**) hand lay-up, (**b**) compression moulding, (**c**) vacuum bagging.

Table 1. V_f values of the composite laminates based on different manufacturing methods.

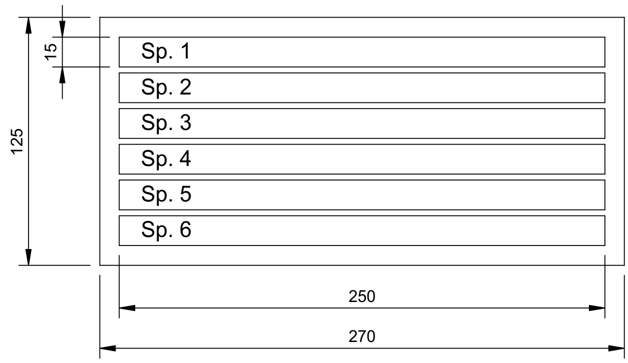
No.	Manufacturing method	Fibre volume fraction value (%)
1	Hand lay-up	34
2	Low-capacity vacuum bagging	38
3	Compression moulding	45
4	High-capacity vacuum bagging	50

2.3 *Density measurement*

The actual and theoretical density values were determined for each of the composite laminates. To determine the actual (experimental) density, the mass and the volume of the control specimen were measured precisely with a 10^{-4} precise scale. Then, the theoretical density was calculated based on the following equation (1) [28];

$$\rho_{ct} = \rho_f V_f + \left(1 - V_f\right)\rho_m \tag{2}$$

where, ρ_{ct}, ρ_f, and ρ_m (kg/m^{-3}) are the theoretical composite, fibre, and matrix density values, respectively, and the V_f (vol.%) is the fibre volume fraction.



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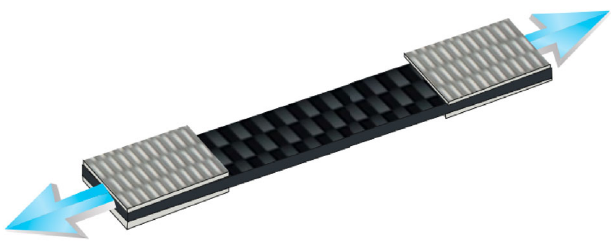

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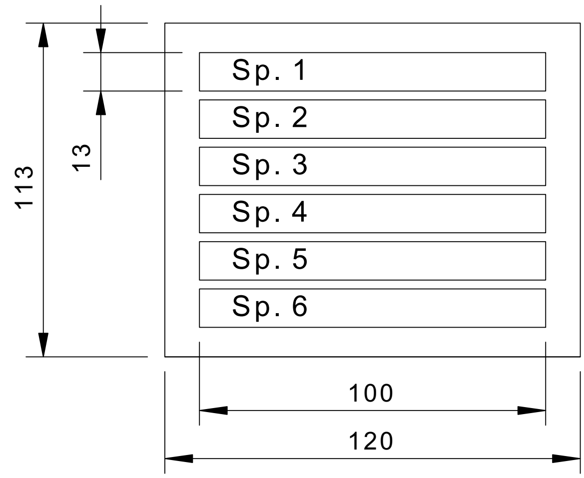
Figure 3. (**a**) Dimensions of the laminate and tensile test specimens, (**b**) Schematic of the testing specimen.



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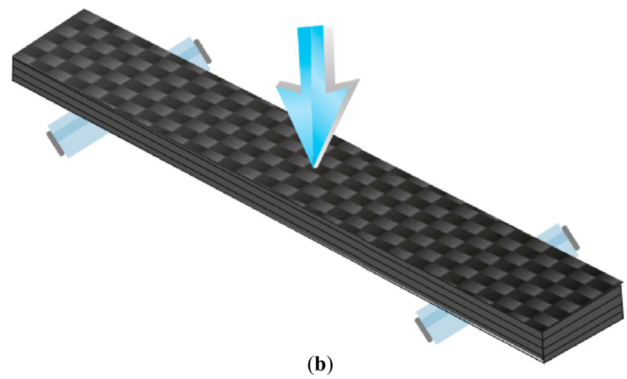


(b)

Figure 4. (**a**) Dimensions of the laminate and flexural test specimens, (**b**) Schematic of the testing specimen (span length is adjusted according to the 60:1 span-to-thickness ratio).

2.4 *Determination of void content*

The percent difference between the actual and the theoretical density values yields the void content within the laminated composites. The determination of the void is made based on equation (2) [28].

$$v = \frac{\rho_{ct} - \rho_{exp}}{\rho_{ct}} \quad (3)$$

where ρ_{exp} (kg.m^{-3}) is the experimental composite density measured from the laminate specimen and ν (vol.%) is the amount of void within the laminate.

2.5 *Tensile tests*

The tensile properties in terms of strength, modulus, and percent elongation at break were determined by performing tensile tests. ASTM D 3039 Standard [29] was applied, and the dimensions of both specimens and produced laminate were presented in figure 3. As seen in figure 3b, the tab elements produced from the E-glass fibre/epoxy composite plates were used to avoid undesired failures. The tests were conducted with Instron 8801 universal testing machine, and the crosshead speed was set to 2 mm.min^{-1}. While five specimens were subjected to tensile tests, the rest was used for density and V_f measurements.

2.6 *Three-point bending tests*

The quasi-static three-point bending tests were applied to determine the flexural strength and modulus of the produced composite laminates. The tests were carried out at a crosshead speed of 1 mm.min^{-1} according to ASTM 7264 Standard [30] using Instron 8801 universal testing machine. Dimensions of the produced composite laminates and the specimens are presented in figure 4. Six specimens were prepared as the case in the tensile tests, the five ones were used for three-point bending tests, and the remaining was for the density and V_f measurements. Due to the effect of different manufacturing methods, the thickness of the specimens was varied. In three-point bending tests, the span-to-thickness ratio is 60:1 as suggested by the ASTM standard, and the span length was adjusted to keep the ratio constant during the tests for the composite laminates. Table 2 illustrates the thickness and the span length of the specimens, which vary depending upon the span-to-thickness ratio of each manufacturing method. As seen in the table, laminate thickness reduces with the compaction

Table 2. The thickness and the span length of the specimens.

Manufacturing method	V_f (%)	Thickness (mm)	Span length (mm)
Hand lay-up	34	1.195	71.70
Low-capacity vacuum bagging	38	1.030	61.08
Compression moulding	45	0.900	54.00
High-capacity vacuum bagging	50	0.820	49.20

Table 3. Theoretical and actual values of the composite densities.

Manufacturing method	V_f (vol.%)	Theoretical density (kg.m^{-3})	Experimental density (kg.m^{-3})
Hand lay-up	34	1.4033	1.2898
Low-capacity vacuum bagging	38	1.4148	1.3098
Compression moulding	45	1.4738	1.4334
High-capacity vacuum bagging	50	1.4900	1.4688

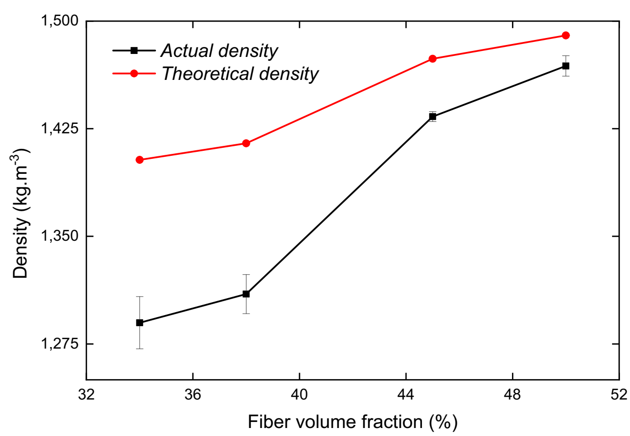


Figure 5. Theoretical and actual density values based on the composites' V_f.

pressure matching the findings of Choudhary and Yalcinkaya [12, 18].

3. Results and discussion

3.1 *Density of composite laminates*

The density of the produced composite laminates was determined with both experimental measurements and theoretical calculations. The results are given in table 3. The theoretical results were obtained higher than the experimental findings as expected since the manufacturing is assumed to be carried out without any defects like voids [12]. The relationship between the theoretical and the experimental (actual) results is presented in figure 5 according to the fibre volume fraction values.

As seen in figure 5, the difference between the actual and theoretical density values deviates from each other for relatively lower fibre volume fraction values. As the V_f values increase, the actual density values get closer to the theoretical values.

3.2 *Void contents within the composite laminates*

The void contents within the produced composite laminates are given in table 4. When compared to the hand lay-up method (figure 2a), the compression moulding (figure 2b) and the high-capacity vacuum bagging (figure 2c) methods allowed removing of the excessive resin effectively, provided to eliminate a significant portion of voids leading to obtaining enhanced composite quality [31]. Yalcinkaya *et al* [18] applied external pressure to improve the resin movement and obtained increased fibre volume fraction, but the void content was increased first, and then it was decreased with the aid of heating during curing. Extracting the excessive resin also provided weight reduction of the composite laminate [32]. Although the hand lay-up method is simple and the cheapest process and has still been used for aeroplanes' seats, shipbuilding, and automotive dashboard, it resulted in the highest percentage of void as indicated in the literature [33, 34]. The amount of void decreases with an increase in V_f values, and it was significantly reduced in the case of applying compression moulding and high-capacity vacuum bagging methods in manufacturing.

Contrary to the V_f - density relationship, the void content is reduced with the increase of the V_f value. Similar findings were obtained by Choudhary *et al* [12]. However, contrary to the expectation, low V_f values were reported for the decreased void content by Mujahid *et al* [14]. Figure 6 shows the change of density and void content depending

Table 4. Void content of the composite laminates according to the manufacturing methods.

Manufacturing method	V_f (vol.%)	Void (vol.%)
Hand lay-up	34	7.43
Low-capacity vacuum bagging	38	6.87
Compression moulding	45	2.63
High-capacity vacuum bagging	50	1.36

upon the fibre volume fraction value. When the two different types of vacuum bagging methods are compared, the varied results may be due to the resin flow rate during the cure cycle. Because the low-capacity vacuum pump could not efficiently provide the resin flow and retarded its flow due to its low-pressure capacity [11], which led to obtaining higher void content within the composite laminate produced with the low-capacity vacuum bagging method. Mehdikhani *et al* [19] also stated that the vacuum level and pressure are the major deterministic factors in void formation.

As seen in figures 5 and 6, the higher value of V_f is a strong indicator of the quality of the composite products. Because when a higher value of V_f is achieved, the density of the composites increases and the difference between the theoretical and actual density values significantly reduces. Moreover, a considerable amount of reduction was provided in void formation. This reduction can also be considered as contribution to the mechanical and thermal properties of the structures [35]. A similar relationship between the void content and the fibre volume fraction was also found by Amirkhosravi *et al* and Talabari *et al* [36, 37]

3.3 *Tensile properties*

The tensile strength and modulus data were determined after performing the mechanical tests. The results were presented by considering the theoretical density (ρ) to reveal the effect of manufacturing methods on the materials' tensile performance. Therefore, figure 7 shows the specific tensile strength ($\sigma^t.\rho^{-1}$) and specific tensile modulus ($E^t.\rho^{-1}$), respectively. Both strength and modulus data increased with the increased fibre volume fractions. Moreover, the composite with 50% V_f made an outstanding contribution to specific tensile properties. The composites with V_f values of 38% and 45% increased the specific tensile strength by 3.25% and 7.45%, respectively, compared to the 34% V_f composite's strength value. The composite yielding 50% V_f has a 40.13% higher specific tensile strength than the composite with the 34% V_f (obtained with hand lay-up). A 16% increment was reported in the literature by applying the VARTM method compared to the hand lay-up process [12]. Therefore, the vacuum bag

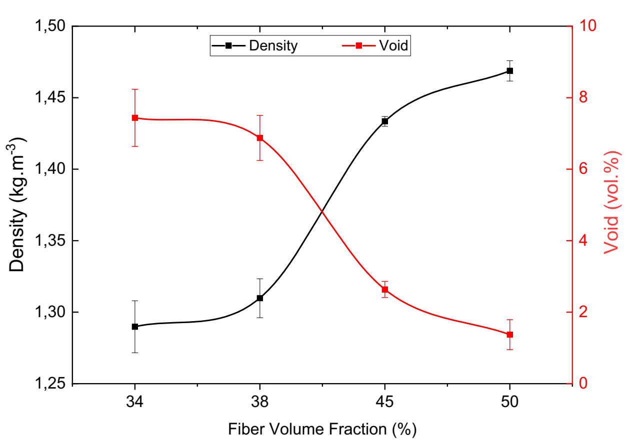


Figure 6. The change of density and void content according to V_f values.

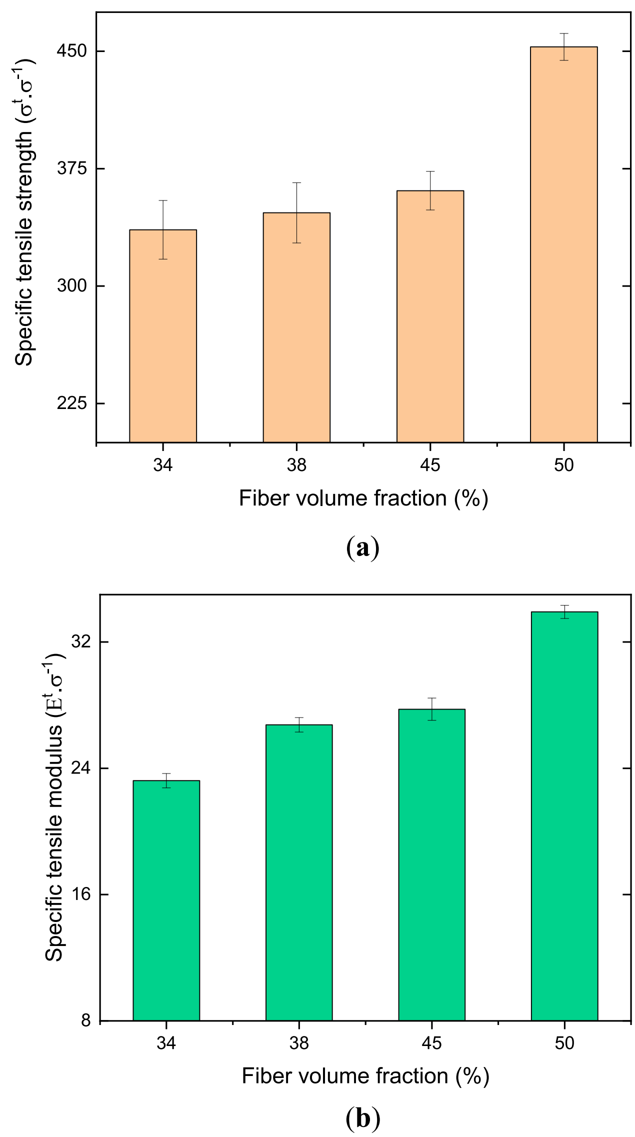


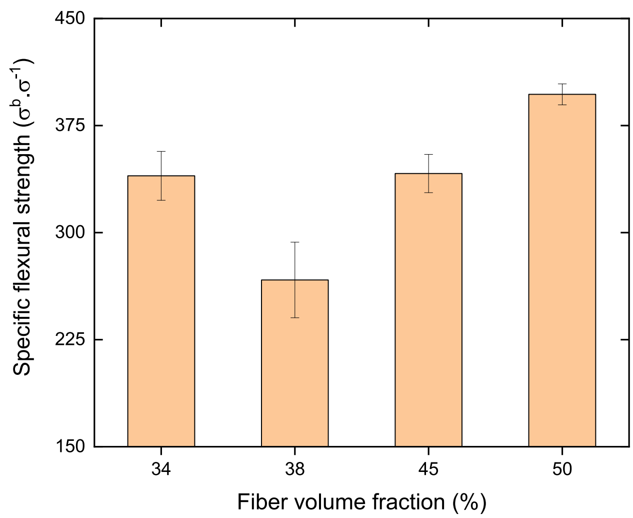
Figure 7. (**a**) Specific tensile strength ($\sigma^t.\rho^{-1}$), (**b**) Specific tensile modulus ($E^t.\rho^{-1}$).

method can provide improved tensile properties compared to the VARTM method.

On the other hand, the specific tensile modulus values were also increased. When compared to the composite produced with hand lay-up (34% V_f), while the 50% V_f composite resulted in 46.05% higher specific tensile modulus, the 45% V_f and 38% V_f composites resulted in an increase of specific tensile modulus data by 19.49% and 15.24%, respectively. The small amount of increase in the specific tensile properties from the composite with 38% V_f to the composite with 45% V_f is due to the higher rate of increase in composites' density. Although Mehidkhani *et al* [19] reported that fibre-dominated longitudinal tensile modulus has been insensitive to the void content, the increase of specific tensile modulus in the present study can be explained by the high rate of reductions in voids. Because the cross-sectional area of the composite laminate decreases in the case of a low-void structure and hence, the tensile strength increases. Additionally, as the void content was found inversely proportional to the V_f, the increment in specific tensile modulus could be due to the increase in V_f value. The higher the V_f, the lower the strain value obtained since it is the fibre-dominated feature of the composite. Similar percentages of increments for both strength and modulus values were also found by Wisojodharmo and Roseno [38] by applying the vacuum infusion method compared to the hand lay-up process. Talabari *et al* [37] indicated that the improvements in tensile strength and the modulus were attributed to the higher V_f value and the less void formation. As the composites' V_f increases, the void content within the structure decreased, leading to better load transfer between the fibres and the matrix [12]. The applied vacuum with a high-capacity vacuum pump contributed to obtaining the highest specific tensile strength and modulus due to the enhanced fibre-matrix interfacial strength [13, 39].

3.4 *Flexural properties*

The flexural strength and modulus data were obtained by performing three-point bending tests. The results were introduced by taking the theoretical density of the laminated composites into account. Therefore, figure 8 depicts the specific flexural strength ($\sigma^b.\rho^{-1}$) and specific flexural modulus ($E^b.\rho^{-1}$) of the composites under three-point bending loading. The composite yielding 50% V_f value produced with the high-capacity vacuum bagging method provided the highest specific strength and modulus data. Specific flexural strength and modulus were increased by 16.78% and 43.95% when compared to the composites produced with the hand lay-up method (V_f: 34%). While the composite with the second-highest V_f (45%) obtained with the compression moulding method yielded a similar specific flexural strength with 34% V_f composite, a slight increase was obtained for the specific flexural modulus. However, compared to 50% V_f composite, its specific flexural strength, and specific flexural modulus values were lower by approximately 14% and 25%, respectively. In the literature, Hagstrand *et al* [40] manufactured unidirectional glass fibre-reinforced polymer matrix composites with compression moulding, obtained 35% V_f, and reported 14 vol.% voids within the laminate leading to poor flexural properties. However, although an increasing trend was obtained for the tensile properties of the composites depending upon their V_f value, the specific flexural strength did not present similar behaviour. This may be due to the inhomogeneous distribution of the voids for the composites produced with a low-capacity vacuum bagging method yielding 38% V_f. The low level of the vacuum caused lower



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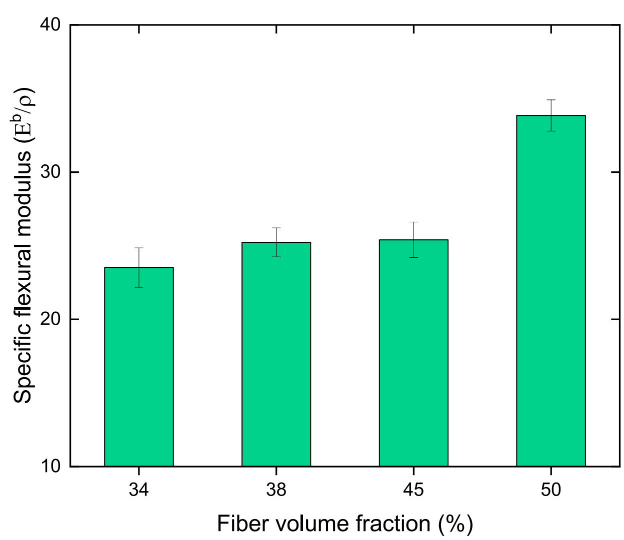

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Figure 8. (**a**) Specific flexural strength ($\sigma^b.\rho^{-1}$), (**b**) Specific flexural modulus ($E^b.\rho^{-1}$).

Table 5. ANOVA results for tensile strength (A: fiber volume fraction).

Source	Sum of squares	df	Mean square	F-value	p-value	
Model	1.27E+05	3	42211.85	70.04	< 0.0001	significant
A-Vf	2376.5	1	2376.5	3.94	0.0645	
A^2	16289.76	1	16289.76	27.03	< 0.0001	
A^3	3344.46	1	3344.46	5.55	0.0316	
Pure error	9643.49	16	602.72			
Cor total	1.36E+05	19				

Table 6. ANOVA results for tensile modulus (A: fiber volume fraction).

Source	Sum of squares	df	Mean square	F-value	p-value	
Model	851.41	3	283.8	393.92	< 0.0001	significant
A-Vf	7.03	1	7.03	9.76	0.0065	
A^2	16.19	1	16.19	22.47	0.0002	
A^3	43.82	1	43.82	60.82	< 0.0001	
Pure error	11.53	16	0.7205			
Cor total	862.93	19				

compact pressure inefficiently over the laminate leading to poor interfacial strength [18], and thus, lower flexural strength-to-density ratio was obtained. While the top side of the specimens was subjected to compressive forces, the bottom side was undergoing tensile loading; therefore, the structure failed at low loadings. The load transfer efficiency became poor [19]. Unlike tensile loading, the load is applied at the midpoint and, the fibre and matrix carry the load in this local area under three-point bending loads. Therefore, the inhomogeneous distribution of voids may affect the specific flexural strength of the composites. But due to the decreased deflection at the break, the specific flexural modulus did not reduce, and it was obtained higher than that of the composites produced with hand lay-up. The deflection determines the strain of the composite laminate and the strain of carbon fiber is much lower than that of the epoxy. It is expected that as the V_f increases, the mechanical properties of the composite laminates get closer to the fiber material. Thus, the deflection of the composite laminate decreases.

Choudhary *et al* [12] also reported that the presence of vacuum pressure provides an increment in composite density; thus, the tensile and flexural strength can be improved. On the other hand, when the void content is supposed to affect the mechanical properties, the present study has shown that the lower the void formation, the higher the tensile and flexural properties. Similar results were presented by Hagstrand *et al* [40]. However, Liu *et al* and Stamopoulos *et al* [41, 42] indicated a significant degradation effect of void on the flexural modulus existed, unlike tensile modulus data. Some what unexpectedly and contradictory to our findings, Mujahid *et al* [14] obtained lower tensile and flexural strength with composites having the lowest void content. As the void is defined as the defect that existed in the composites, the mechanical properties of composites are expected to be higher at the low content of void and high fibre volume fraction as the case obtained in the present study.

4. Single objective optimization with ANOVA

The effect of fibre volume fraction on the polymer composites' laminate density and mechanical properties was investigated with ANOVA. Empirical equations were obtained to calculate the tensile and flexural strength and modulus data and the composites' density depending upon the composites' V_f values by conducting single-objective optimization. The V_f provides insights into the quality of the product and the success of the manufacturing. Furthermore, it substantially affects the mechanical properties. Two-way ANOVA was performed, and Response Surface Methodology (RSM) was applied to generate the mathematical models. Based on the results given in table 5–9, the p-values were obtained smaller than 0.05, and the constructed models were found statistically significant based on a confidence interval of 95%.

As given in table 10, the high values of adjusted and predicted correlation coefficients (R^2) of the constructed models for tensile and flexural properties and the composite density confirmed that the mechanical properties and the density could be predictable, and the models can strongly explain the significant changes. Both the adjusted and predicted R^2 values are in good agreement. Therefore, the

Table 7. ANOVA results for flexural strength (A: fibre volume fraction).

Source	Sum of squares	df	Mean square	F-value	p-value	
Model	1.16E+05	3	38728.98	49.71	< 0.0001	significant
A-Vf	40232.39	1	40232.39	51.64	< 0.0001	
A^2	38003.91	1	38003.91	48.78	< 0.0001	
A^3	16024.69	1	16024.69	20.57	0.0003	
Pure error	12464.96	16	779.06			
Cor total	1.29E+05	19				

Table 8. ANOVA results for flexural modulus (A: fibre volume fraction).

Source	Sum of squares	df	Mean square	F-value	p-value	
Model	900.72	3	300.24	86.42	< 0.0001	significant
A-Vf	1.78	1	1.78	0.5113	0.4849	
A^2	116.44	1	116.44	33.51	< 0.0001	
A^3	57.44	1	57.44	16.53	0.0009	
Pure error	55.59	16	3.47			
Cor total	956.31	19				

Table 9. ANOVA results for composites' density (A: fibre volume fraction).

Source	Sum of squares	df	Mean square	F-value	p-value	
Model	0.0234	3	0.0078	91.04	< 0.0001	significant
A-Vf	0.0059	1	0.0059	69.16	< 0.0001	
A^2	0	1	0	0.1272	0.7276	
A^3	0.001	1	0.001	11.18	0.0058	
Pure error	0.001	12	0.0001			
Cor total	0.0244	15				

Table 10. Adjusted and predicted correlation coefficient (R^2) values.

Response	Adjusted R^2 (%)	Predicted R^2 (%)
Tensile strength (MPa)	91.60	88.94
Tensile modulus (GPa)	98.41	97.91
Flexural strength (MPa)	88.49	84.86
Flexural modulus (GPa)	93.10	90.92
Density (kg.m^{-3})	94.74	92.52

mechanical properties and composites' density can approximately be predicted by the empirical equations developed by the regression analysis depending upon the constructed models. Table 11 provides the empirical equations for each of the mechanical properties and composite density as a function of fibre volume fraction (V_f). Several case studies were performed to verify the equations, as given in table 12. The results of four examples (V_f: 34%, 38%, 45%, and 50%) were directly taken from this experimental study. The results obtained from the empirical equations are in excellent agreement with the experimental findings. The differences are below 1% (between 0.2% and 0.9%).

Now, the derivation of a single-objective optimization equation is possible depending upon the empirical equations given in table 11. The objective is to maximize the ratio of mechanical properties of the composite to its density. The objective functions, given in Eq. 3, can be obtained by arranging the equations provided in table 11 as follow;

$$MaxZ = \frac{Mechanical\,Property}{Density} \quad (4)$$

The objective functions for each of the mechanical properties are given in table 13.

5. Conclusion

Four different kinds of composite laminates were produced with three different manufacturing methods and using two different vacuum characteristics. The vacuum bagging

Table 11. Empirical equations to predict the mechanical properties (V_f: fibre volume fraction).

Response		Empirical equations
Tensile strength (MPa)	=	$-6069.9297 + 504.7420.V_f - 12.9901.V_f^2 + 0.1119.V_f^3$
Tensile modulus (GPa)	=	$-850.5526 + 65.1354.V_f - 1.5785.V_f^2 + 0.0128.V_f^3$
Flexural strength (MPa)	=	$+20584.2896 - 1414.6627.V_f + 32.5389.V_f^2 - 0.2449.V_f^3$
Flexural modulus (GPa)	=	$-892.0069 + 69.8865.V_f - 1.7537.V_f^2 + 0.0147.V_f^3$
Density ($kg.m^{-3}$)	=	$+6.04694 - 0.346875.V_f + 0.00846.V_f^2 - 0.000067.V_f^3$

Table 12. Case studies to verify the empirical equations according to V_f values of the laminates.

V_f (vol.%)	σ^t (Mpa)	E^t (Mpa)	σ^b (Mpa)	E^b (Mpa)	ρ ($kg.m^{-3}$)	$\sigma^t.\rho^{-1}$	$E^t.\rho^{-1}$	$\sigma^b.\rho^{-1}$	$E^b.\rho^{-1}$
34	471.37	32.58	476.89	33.02	1.400	336.80	23.28	340.74	23.59
36	484.65	36.00	402.83	35.05	1.398	346.76	25.75	288.22	25.08
38	490.66	37.85	377.52	35.72	1.406	349.10	26.93	268.60	25.41
40	494.76	38.75	389.22	35.73	1.420	348.44	27.29	274.11	25.16
42	502.33	39.32	426.17	35.78	1.438	349.39	27.35	296.41	24.89
45	531.92	40.88	503.22	37.48	1.464	363.41	27.93	343.80	25.60
48	599.52	45.15	570.97	43.23	1.479	405.32	30.52	386.02	29.23
50	674.65	50.52	591.38	50.50	1.478	456.40	34.18	400.07	34.16

Table 13. Objective functions for the mechanical properties.

Objective	Function	Eq.
$Max.\frac{\sigma^t}{\rho} =$	$\frac{-6069.9297+504.7420.V_f-12.9901.V_f^2+0.1119.V_f^3}{6.04694-0.346875.V_f+0,00846.V_f^2-0.000067.V_f^3}$	(5)
$Max.\frac{E^t}{\rho} =$	$\frac{-850.5526+65.1354.V_f-1.5785.V_f^2+0.0128.V_f^3}{6.04694-0.346875.V_f+0,00846.V_f^2-0.000067.V_f^3}$	(6)
$Max.\frac{\sigma^b}{\rho} =$	$\frac{20584.2896-1414.6627.V_f+32.5389.V_f^2-0.2449.V_f^3}{6.04694-0.346875.V_f+0,00846.V_f^2-0.000067.V_f^3}$	(7)
$Max.\frac{E^b}{\rho} =$	$\frac{-892.0069+69.8865.V_f-1.7537.V_f^2+0.0147.V_f^3}{6.04694-0.346875.V_f+0,00846.V_f^2-0.000067.V_f^3}$	(8)

method with high vacuum characteristics (HVB) considerably enhanced the physical and mechanical properties when compared to low-capacity vacuum bagging (LVB), compression moulding (CM), and hand lay-up (HL) methods. The following conclusions can be drawn from the study;

- The manufacturing method is an essential affecting factor in the physical and mechanical characteristics of laminated composites. The composites produced with a high fibre volume fraction (V_f) value provide less void content, higher density, and better fibre and matrix interfacial strength, leading to a more uniform load distribution between the fibre and the matrix and higher mechanical properties. Therefore, the V_f value is a strong indicator of the composite product quality.
- The rate of increase in laminate density is very high in the 38–45% V_f interval. At the same interval, the rate of reduction in void formation is very high. Both the CM and HVB provided adequate compaction pressure and efficient resin flow. Compared to the HL method, the reductions in void content in LVB, CM, and HVB were 7.54%, 64.60%, and 81.70%, respectively.
- The difference between the actual and the theoretical densities reduced more as the V_f value increased.
- The specific tensile and flexural modulus of the composites were obtained in the order of HVB> CM>LVB>HL. While the specific tensile strengths were obtained in the order of HVB>CM>LVB>HL, the specific flexural strengths were obtained in the order of HVB>CM > HL>LVB.
- The application of two different vacuum bagging showed that the enhancement in compaction pressure contributed to resin flow, high V_f, and reduction of voids in the composite structures.
- The lower mechanical properties associated with the amount of voids within the composite laminates lead to lower matrix-dominated properties, which adversely affect the interfacial strength, delamination, and fibre-matrix debonding. Such composites are also susceptible to environmental effects like moisture absorption. Therefore, it is essential to apply an optimized manufacturing technique, resulting in lower void content and higher V_f.
- Empirical equations were derived to compute the laminate density and mechanical properties (tensile and flexural) of composites as a function of V_f. The equations were obtained with very high correlation

coefficient (R^2) values and verified by the case studies. Therefore, the laminate density, tensile and flexural strength, and tensile and flexural modulus can be predicted.

- A single objective optimization was conducted to maximize the ratio of mechanical strength and modulus to laminate density.

For future studies, the viscosity effects of several matrix materials, compaction pressure, fibre intensity in tow, and laminate thickness can be considered the affecting factors in investigating the void formation.

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References

[1] Vedernikov A, Safonov A, Tucci F, Carlone P and Akhatov I 2020 Pultruded materials and structures: a review. *J. Compos. Mater.* 54: 408–4117

[2] Al-saadi A U, Aravinthan T and Lokuge W 2018 Structural applications of fibre reinforced polymer (FRP) composite tubes: a review of columns members. *Compos. Struct.* 204: 513–524

[3] Sevkat E, Brahimi M and Berri S 2012 The bearing strength of pin loaded woven composites manufactured by vacuum assisted resin transfer moulding and hand lay-up techniques. *Polym. Polym. Compos.* 20: 32–332

[4] Sas H S, Šimáček P and Advani S G 2015 A methodology to reduce variability during vacuum infusion with optimized design of distribution media. *Compos. Part A* 78: 223–233

[5] Bere P, Sabau E, Dudescu C, Neamţu C and Fărtan M 2019 Experimental research regarding carbon fiber/epoxy material manufactured by autoclave process. In: *MATEC Web of Conferences.*, vol. 299, p. 06005

[6] Sevkat E and Brahimi M 2011 The bearing strength of pin loaded woven composites manufactured by vacuum assisted resin transfer moulding and hand lay-up techniques. *Procedia Eng.* 10: 153–158

[7] de Lumley T, Mathieu F, Cornet D, Gueuning D and Hille N 2019 Out-of-autoclave process and automation: a successful path to highly integrated and cost efficient composite wing moveables

[8] Kim J H, Kim H J, Chyun I B, An J J and Kim J H 2014 Characteristic analysis of carbon FRP tube changed cross-sectional shape by bending load. *Mater. Res. Innovations.* 18: 328–332

[9] Uzay Ç and Geren N 2020 Advanced technologies for fiber reinforced polymer composite manufacturing: a review. *KSI Unv. J. Eng. Sci.* 23: 245–257

[10] Durgun I 2014 Composite parts production with hand lay method. In: *Conference: 7th Engineering and Technology Symposium - MTS7*

[11] Park S Y, Choi C H, Choi W J and Hwang S S 2019 A comparison of the properties of carbon fiber epoxy composites produced by non-autoclave with vacuum bag only prepreg and autoclave process. *Appl. Compos. Mater.* 26: 187–204

[12] Choudhary M, Sharma A, Dwivedi M and Patnaik A 2019 A comparative study of the physical, mechanical and thermo-mechanical behavior of GFRP composite based on fabrication techniques. *Fibers Polym.* 20: 823–831

[13] Kim S-Y, Shim C S, Sturtevant C, Kim D and Song H C 2014 Mechanical properties and production quality of hand-layup and vacuum infusion processed hybrid composite materials for GFRP marine structures. *Int. J. Nav. Archit. Ocean Eng.* 6: 723–736

[14] Mujahid Y, Sallih N, Abdullah M Z and Mustapha M 2021 Effects of processing parameters for vacuum-bag-only method on void content and mechanical properties of laminated composites. *Polym. Compos.* 42: 567–582

[15] Zhang K, Gu Y and Zhang Z, 2014 Effect of rapid curing process on the properties of carbon fiber/epoxy composite fabricated using vacuum assisted resin infusion molding. *Mater. Des.* 54: 624–631

[16] Abdelal N and Donaldson S L 2017 Comparison of methods for the characterization of voids in glass fiber composites. *J. Compos. Mater.* 52: 487–501

[17] Lambert J, Chambers A R, Sinclair I and Spearing S M 2012 3D damage characterisation and the role of voids in the fatigue of wind turbine blade materials. *Compos. Sci. Technol.* 72: 337–343

[18] Yalcinkaya M A, Sozer E M and Altan M C 2019 Effect of external pressure and resin flushing on reduction of process-induced voids and enhancement of laminate quality in heated-VARTM. *Compos. Part A* 121: 353–364

[19] Mehdikhani M, Gorbatikh L, Verpoest I and Lomov S V 2018 Voids in fiber-reinforced polymer composites: A review on their formation, characteristics, and effects on mechanical performance. *J. Compos. Mater.* 53: 1579–1669

[20] Kim D, Hennigan D J and Beavers K D 2010 Effect of fabrication processes on mechanical properties of glass fiber reinforced polymer composites for 49 meter (160 foot) recreational yachts. *Int. J. Nav. Archit. Ocean Eng.* 2: 45–56

[21] Dost Kimya 2017 *Technical Data Sheet, Carbon Fabric – 200gr/sqm 3K Plain. Rev.2.2, Turkey*

[22] Bhattacharjee A and Roy H 2020 Assessment of tensile and damping behaviour of hybrid particle/woven fibre/polymer composites. *Compos. Struct.* 244: 112231

[23] Kubo G, Matsuda T and Sato Y 2018 A novel basic cell modeling method for elastic-viscoplastic homogenization analysis of plain-woven laminates with nesting. *Int. J. Mech. Sci.* 146–147: 497–506

[24] Dost Kimya 2009 Laminating Resin MGSTM L160 and Hardener H160, Hexion. In: *Technical Data Sheet*. The Netherlands

[25] Uzay Ç and Geren N 2020 Effect of stainless-steel wire mesh embedded into fibre-reinforced polymer facings on flexural characteristics of sandwich structures. *J. Reinf. Plast. Compos.* 39: 613–633

[26] Boztepe M, Uzay Ç and Bayramoglu M 2016 Investigation of tensile behavior of woven carbon, glass and hybrid fiber composites. In: *Conference of the International Journal of Arts & Sciences*

[27] International A 2017 Test methods for constituent content of composite materials. In: *ASTM Standard D 3171–99*
[28] Kaw A K 2005 *Mechanics of Composite Materials*. CRC Press
[29] ASTM I 2017 Standard test method for tensile properties of polymer matrix composite materials. In: *ASTM D3039/ D3039M-17*. West Conshohocken, PA
[30] ASTM I 2021 Standard test method for flexural properties of polymer matrix composite materials. In: *ASTM D7264/ D7264M-21*. West Conshohocken, PA
[31] Scalici T, Pitarresi G, Badagliacco D, Fiore V and Valenza A 2016 Mechanical properties of basalt fiber reinforced composites manufactured with different vacuum assisted impregnation techniques. *Compos. Part B* 104: 35–43
[32] Tzetzis D and Hogg P J 2008 Experimental and finite element analysis on the performance of vacuum-assisted resin infused single scarf repairs. *Mater. Des.* 29: 436–449
[33] Kedari V, Farah B and Hsiao K T 2011 Effects of vacuum pressure, inlet pressure, and mold temperature on the void content, volume fraction of polyester/e-glass fiber composites manufactured with VARTM process. *J. Compos. Mater.* 45: 2727–2742
[34] Wonderly C, Grenestedt J, Fernlund G and Cěpus E 2005 Comparison of mechanical properties of glass fiber/vinyl ester and carbon fiber/vinyl ester composites. *Composites, Part B* 36: 417–426
[35] Bureau M N and Denault J 2004 Fatigue resistance of continuous glass fiber/polypropylene composites: consolidation dependence. *Compos. Sci. Technol.* 64: 1785–1794
[36] Amirkhosravi M, Pishvar M and Altan M C 2017 Improving laminate quality in wet lay-up/vacuum bag processes by magnet assisted composite manufacturing (MACM). *Compos. Part A* 98: 227–237
[37] Talabari A, Alaei M and Shalian H 2019 Experimental investigation of tensile properties in a glass/epoxy sample manufactured by vacuum infusion, vacuum bag and hand layup process. *Rev. Compos. Mater. Av.* 29: 179–182
[38] Wisojodharmo L A and Roseno S 2012 The use of vacuum assisted resin infusion process onthe manufacturing of wind blade composites. *J. Mater. Sci. Eng.* 2: 74–78
[39] Pawar M, Patnaik A and Nagar R 2016 Mechanical and thermo-mechanical analysis based numerical simulation of granite powder filled polymer composites for wind turbine blade. *Fibers Polym.* 17: 1078–1089
[40] Hagstrand P O, Bonjour F and Månson J A E 2005 The influence of void content on the structural flexural performance of unidirectional glass fibre reinforced polypropylene composites. *Compos. Part A* 36: 705–714
[41] Liu L, Zhang B-M, Wang D-F and Wu Z-J 2006 Effects of cure cycles on void content and mechanical properties of composite laminates. *Compos. Struct.* 73: 303–309
[42] Stamopoulos A G, Tserpes K I, Prucha P and Vavrik D 2015 Evaluation of porosity effects on the mechanical properties of carbon fiber-reinforced plastic unidirectional laminates by X-ray computed tomography and mechanical testing. *J. Compos. Mater.* 50: 2087–2098