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Process Parameters Optimization And Characterization Of RTM Manufacturing Process For High Performance Composites.

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Abstract
Due to its improved mechanical qualities over conventional materials, glass fiber reinforced composites are increasingly in demand for use in the aerospace, military, transportation, and other industries. The experiments in the current investigations were carried out in accordance with the design of experiments (DOE). In order to generate high-quality E-glass chopped strand/polyester composites with three different volume fractions at five chosen resin injection pressures, a customized RTM with central resin injection system was created. To observe the resin being impregnated into the reinforcement and measure the filling time, flow front velocity, Reynolds number, permeability, and number of voids, a flow visualization technique was used. The mechanical parameters of the molded laminates (tensile, flexural, and impact strengths) were tested in accordance with ASTM standards. Analysis of variance (ANOVA) was used to investigate the interactions between the process variables (number of layers and resin injection pressure) and their effects on the mechanical properties. In the current study, three different composites were made at five different resin injection pressures (P1 = 0.196 MPa, P2 = 0.245 MPa, P3 = 0.294 MPa, P4 = 0.343 MPa, and P5 = 0.392 MPa) using E-glass chopped strand fiber preforms (with 4, 5 and 6 layers) reinforced with polyester resin. Typically fluctuating between 0.2 MPa and 2 MPa, polyester resin was permitted to flow via the central resin port in this RTM.

Keywords: RTM Method, Tensile Strength, Microstructure Analysis, ANOVA.

1. Introduction

In the past, wood and animal bones were used as natural composites for farming, fishing, and hunting. The traditional bone knife that was kept at the National History Museum in 10000 BC is an example [1].The first composite human was created during the mummification of Egypt circa 3000 BC. In the year 2000 BC, cow excrement and straw were combined to create bricks [2].Manufacturers of automotive and aeronautical parts were compelled to improve fuel economy without raising the price or weight of their products. Glass fiber reinforced polymer (GFRP) composites were used in the sports industry to replace the traditional materials [3]. Over the past 35 years, GFRP composites have been widely employed for pressure tanks, aircraft panels, and fiberglass boats. Glass fibers are the first known fibers in advanced composites companionable with polyester and epoxy resins [4]. The GFRP composites are made of glass fiber reinforced with plastic material. They can be designed to obtain essential directional properties to suit the loading conditions. Mechanical strength for GFR composites is higher than for any main

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plastic material [5].They outperform metals in terms of strength and weight. GFRP composites can definitely be molded without the need of a heater. Their strength properties are somewhat lower than carbon fiber. Commercial, military, and space applications have been paying close attention to GFRP composites. High-performance airplanes, boats, autos, wind turbine blades, ships, water tanks, roofing, pipelines, door skins, sports cars, and boats are just a few of the broad uses for GFRP composites [6]. Composite parts can be made using a variety of techniques. However, many were improved to address issues with manufacturing fiber-reinforced polymers [7]. Therefore, the materials, part design, and application all influence the technique choice for a given part [8]. Either open or closed molding is used to create the composite. Resin transfer molding (RTM) has become a popular manufacturing technique because it can generate high-quality goods at a reasonable price [9].This technique has a reasonable cost, good control over volatile emissions into the atmosphere, and flexibility [10].

1.1 Suggested Work

In the current study, a modified RTM with a central resin injection port was created to test different resin injection pressures and layer counts to evaluate the process parameters [11]. Tensile, flexural, and impact strengths were calculated using ASTM standards to determine the mechanical properties. The SEM studies were conducted to see how the fiber and matrix interacted at the interface. The interaction effect of process factors on the mechanical characteristics of the composite was investigated using analysis of variance (ANOVA) [12]. RTM Worx, a commercial simulation program, was used to run simulations in order to estimate resin impregnation or filling times. Utilizing TLBO and artificial neural networks (ANN), the optimization of process parameters on mechanical properties was done [13].

2. Material and Methods

Fiber pre-forms are inserted into a mould during the RTM process. The mold is sealed, and resin is pumped into the mold cavity at a specific pressure [14].The resin is allowed to cure. Due to reinforcing types and their intricate interlayer interactions, several resin flow patterns can be produced during production. However, injection and vent valves are precisely positioned for optimal resin flow patterns. RTM process parameters such resin injection pressure, filling time, flow front velocity, permeability, Reynolds number, and void content, and fiber volume percentage should be carefully chosen for high-quality composites [15].The schematic representation of the resin transfer molding system is shown in Figure 1.

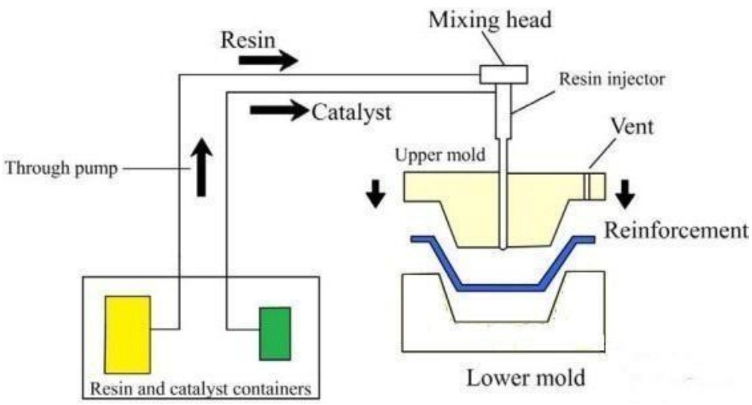

Figure 1: Schematic Diagram of Resin Transfer Mold [16].

2.1 The significance of process variables:

More than any other manufacturing method, RTM offers cost benefits in both labor and materials. The choice of improper process parameters could cause issues with correlating the impact of those parameters on the quality of the finished product. A proper selection of process parameters yields a molded product of high quality [17]. The technique of mould filling is crucial for producing composite components of sound quality. The mould filling time depends on the resin injection pressure. As the injection pressure rises, a gap forms between the top of the mold and cavity. Additionally, the

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composite's thickness rises as well [18]. The mold deforms, fiber washout takes place at the inflow port, and voids start to form. The filling time is prolonged by low injection pressure. This might have an impact on the fiber's wettability and permeability, which impair the product's performance [19]. Therefore a moderate injection pressure and filling time are essential factors. Additionally, the location of the injection port is necessary to prevent a significant issue like fiber wash out and to maintain the desired quality of the composite components. To prevent issues with gelation, the injection pressure should not be too low. Injection pressure affects the speed of the resin and the clamping forces in the mold [20]. This injection pressure modifies the resin's distribution to prevent voids from impairing the composite's mechanical qualities. In the RTM process, resin enters fiber beds with smaller fiber volume percentages more quickly and easily [21]. Variations in fiber volume percentage have an impact on the flow front velocity over time and result in edge effects at the top and bottom of soft-mold covers. When the fiber volume fraction falls, the volume fraction of voids rises. As a result, the volume percentage of the fiber and its mechanical performance of the composite depend [22].Since it describes the preform's therein flow and wettability, permeability is the crucial parameter in the RTM process. When the permeability and resin injection pressure both rise, the filling time reduces. Number of voids rises as a result [23]. The composite strength is decreased when there are voids. As a result, preform permeability affects how well laminates operate. Reynolds number, which is influenced by the flow front velocity [24], resin viscosity, and type of reinforcing, serves as a defining factor for flow patterns. For the best possible production process, a numerical tool is preferred to determine the injection strategy, flow behavior, pressure distribution, permeability, and impregnation time [25].

2.2 Optimization of Process Parameters

In the RTM process, numerous process factors are used as input variables for resin impregnation and curing, which affect the composite's quality. In reality, the composition of the composites is customized based on input factors like the number of layers, resin injection pressure, filling time, flow front velocity, flow rate, mould temperature, melt temperature, resin viscosity, permeability, and volume fraction of fiber, porosity, and type of manufacturing process. All of these factors interact with one another and establish the relationships needed to create mathematical equations, forecast reactions, and determine the best variables that affect composite quality. The optimization approaches are suitably applied to reduce the cost of composite manufacturing and maximize mechanical performance while satisfying a particular set of design limitations. For the optimal design of composite component, the structural requirements and the process should be optimized individually. FRP composite fabrication calls for an appropriate manufacturing process. One of the promising methods for producing big, complicated three-dimensional components with good mechanical performance, tight dimensional tolerance, and high surface quality is resin transfer molding (RTM). A good design using RTM method enables the manufacturing of cost-effective structural parts in medium volume quantities with inexpensive tooling. Hence in the present work a customized RTM has been fabricated to produce GFRP composites. When designing and manufacturing composite structures, decision-making is based on the tensile strength. The matrix has a higher degree of elongation than the fiber, which often has more strength and stiffness. These two constituents combined give a FRP composite with tensile characteristics positioned between the two constituents. Thus, static tensile testing is required to determine mechanical properties. For composite designers, the flexural strength is crucial because the resin generates cavities, and these cavities experience stress when subjected to tensile and compressive pressures. The three-point bend test is preferred for flexural strength since it accurately describes materials that are inexpensive. The sample is easy to prepare. Testing includes environmental adaptability, dependability with cyclic loading, and fracture toughness for composites subjected to simultaneous shear, compression, and tension. In an impact test, the machine gives the specimen kinetic energy to start the fracture and sustain it until the specimen breaks. The work required to shatter a test sample is measured by the impact energy. In an effort to create a high-quality composite, research has been done to determine how resin injection pressure and fiber volume fraction

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affect several process characteristics, including filling time, flow front velocity, Reynolds number, and permeability. Also addressed was the interaction between the input variables (number of layers and injection pressure) and the outcomes (tensile, flexural, and impact strengths).

3 Experimental Procedures

3.1 Raw Materials of Composites

In the current experiments, reinforcement was provided by the E-glass chopped strand fiber mat (CSM of 450 gsm, Code: M6450-104) from M/S Saint Gobain Vetrotex India Limited, Hyderabad, Telangana, India. The catalyst (methylethylketone peroxide), cobalt napthanate, and resin (Polyester of viscosity 450–50Cp) were all provided by M/S Mechemco Industries in Mumbai, India. The efficient mechanical characteristics, reduced weight, low cost, and corrosion resistance of the polyester resin led to its selection as shown in the Table 1 and Table2.

Table 1: Properties of chopped strand mat

Property	Value	Test method
Glass content(%)	25-40	BS2782
Tensile strength	63-140	BS2782
Flexural strength(MPa)	140-250	BS2782
Flexural modulus(GPa)	5-8	BS2782

Table 2: Properties of general purpose polyester resin

Properties	Cast	Laminate
Glass content[w/w]%	-	40-45
Specificgravity@25^0C	1.23	1.59
Tensile strength(MPa)	60	150
Tensile modulus(GPa)	3.4	8.5
Tensile elongation at break (%)	2.00	2.3
Flexural strength(MPa)	115	160
Flexural modulus (GPa)	3.7	10.5
Compressive strength(MPa)	115	160

3.2 Production of Custom Resin Transfer Molds

The equipment was made to allow the resin to flow to all areas of the preform in order to completely wet it. The resin transfer mold is different from the regulatory mold. The process of filling a mold was studied through a series of flow tests. To accomplish this, an aluminum square mold (H30 grade-6082) was created to make laminate with dimensions of 400 mm × 400 mm × 5 mm. The square, translucent acrylic sheet and lid that made up the mold. Grid lines in squares were present on the acrylic sheet. To prevent the resin leakage, a gasket was added between the acrylic sheet and the bottom flat plate. The square hollow lid was placed on the acrylic sheet and fastened to the bottom plate of the mold to seal it. The mold was made of a square stand made of mild steel (AISI 1040). The minor grid lines were separated by 1 mm. The principal gridlines were drawn at intervals of 10 mm. A resin injecting port was placed in the middle of the acrylic plate. To let the extra resin out, two outlet ports were placed at the diagonal's opposing corners. The resin injection and outlet ports were 200 mm apart. Figure 2 depicts the schematic diagram of a customized RTM.

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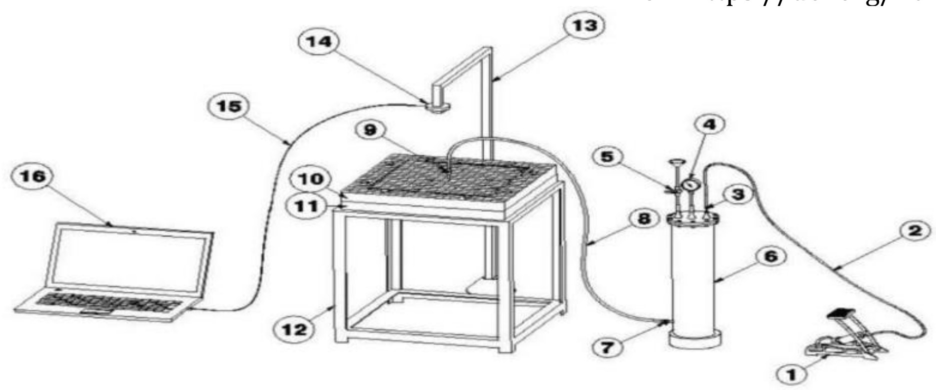

Figure 2: Schematic diagram of customized resin transfer mould.

1	Air pump	9	Resin mixture injection port cum control valve
2	Hosepipe	10	Acrylic sheet
3	Air valve	11	Aluminum mold
4	Pressure gauge	12	M.S. stand
5	Resin mixture entering valve	13	Angular stand
6	Cylindrical resin tank	14	Webcam
7	Flow control valve	15	USB cable connecting web camand PC
8	Rubber tube	16	Personal computer (PC)

Due to measurement inaccuracy, the resin injection pressure instead from pressure gauge and it needs calibration. Here, the measurement error is defined as the discrepancy between the quantity's measured value and its true value. Such errors occur more frequently when a gadget is in use for a longer period of time. The applied pressure must match the pressure inside the RTM cavity. By attaching a Bourdon tube pressure gauge to one of the outlet ports, this was discovered. The pressure gauge needs to be calibrated primarily to ensure its dependability. The air from the foot-operated pump enters the cylindrical resin tank with a 3-liter capacity after passing through the hose tubing and air valve at the proper injection pressure. A pressure gauge with a capacity of 0.98 MPa (and a minimum of 0.0196 MPa) was put on the cylindrical resin tank to measure the pressure of resin flowing through the flow control valve into the mold. Figure 3 (a) depicts the modified RTM that was created for the current research. As it leaves the inlet port, the resin mixture spreads across the entirety of the mold as it enters the reinforcement in a thickness-direction, as shown in Figure 3 (b). A webcam suspended from an angular stand to be located above the grid lines was used to capture the distance that the resin mixture traveled across the grid lines. The webcam sends data to the personal computer. The mold filling time was calculated using this collected data and a flow visualization approach.

To impregnate the fabric in RTM, thermoset resin is allowed to flow under injection pressure that normally ranges between 0.2 MPa and 2 MPa. In order to manufacture the laminates, resin injection pressures between 0.2 MPa and 2 MPa were chosen for the current experiments. The laminates were molded with three distinct preforms. A 4-layer preform was included in the first-place laminate. According to the second and third types each had preforms with five and six layers, respectively. Each of these laminates was created with the respective resin injection pressures P1 (equal to 0.196 MPa), P2 (equal to 0.245 MPa), P3 (equal to 0.294 MPa), P4 (equal to 0.343 MPa), and P5 (equal to 0.392 MPa). No edge effect was observed during trials since the performances were trimmed to fit the size of the mould cavity. According to, dry spots started to form at resin injection pressures greater than 83 kPa. Although the chosen resin injection pressures in the present studies were not higher than 83 kPa, dry patches nor fiber washout emerged.

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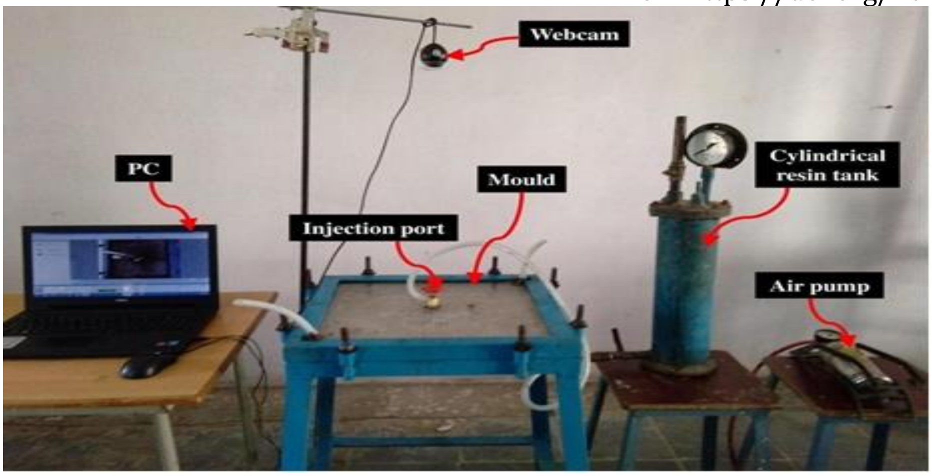
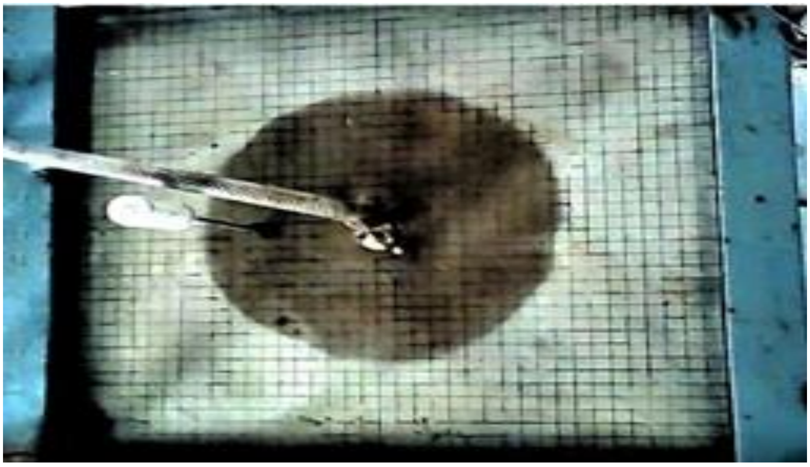


(a)



(b)

Figure 3: Experimental setup (a) customized resin transfer mould and (b) resin flow pattern.

3.3 Static Tensile test:

Typically, a dog bone or rectangular-shaped specimen is taken for tensile testing. The five types of specimen geometries are defined by ASTM D638-08 standards. They are the types I, II, III, IV, and V specimens for reinforced composites that are rigid, semi-rigid, and non-rigid. When testing material with a thickness of 7 mm or less, type I specimens must be used. The current lamination is 5 mm thick. As a result, type I geometry was selected for the tensile testing. Figure 4 displays a randomly chosen group of GFRP specimens used for static tensile tests.

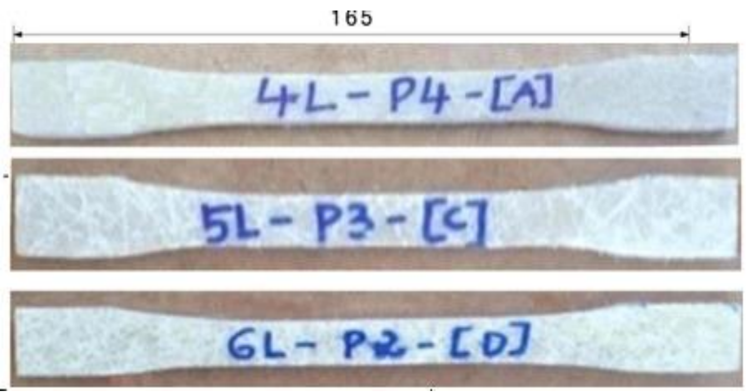


Figure 4: Geometry of tensile specimen as per ASTMD638-08 type.

The universal testing machine (Figure 5) of capacity 100 kN (Deepak Poly Plast; Model DTRX35) was gradually loaded in tension with the GFRP test coupons. At a cross head speed of 2 mm/min, the load was applied. The specimen's displacement with respect to the applied tensile load was noted. Every sample cracked in the middle of the gauge length. Using Equation (1),

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the tensile strength was calculated using the net cross-sectional area taken into account in the proportion of gauge length.

Tensile strength, $\sigma_t = P/A$…………… (1) [22]

Where P is the maximum force applied at the cross sectional area.

Figure 5: GFRP composite specimens under tension in UTM.

3.4 Examination by Scanning Electron Microscope (SEM)

A SEM is an electron microscope that produces images by scanning a surface with a concentrated electron beam. The electrons interact with the sample's atoms to produce a range of signals that carry data on the sample's surface topography and composition. Figure 3.12 displays the SEM apparatus that was used. It is a Carl ZEISS EVO series model with a resolution of 1 nm at 15 kV and a magnification range of 12X to 1000KX.After mechanical testing; the glass fiber reinforced polyester composite specimens were sectioned. The sectioned faces were polished, cleaned with a dry cloth, and washed with distilled water. The most popular coating for non-conductive samples used in conventional SEM applications is gold. A conducting surface is required to interact with the bombardment electron beam. As a result, gold was sprayed on the surface of each specimen to be analyzed. They were subsequently examined using a scanning electron microscope (SEM) to see how well the fiber adhered to the matrix and any resin-rich locations as shown in the Figure 6.

Figure 6: Scanning electron microscope.

ANOVA was carried out at a confidence level of 95% in order to assess the Reynolds number, void content in the material, tensile, flexural, and impact strengths acquired from experiments. Sources with P values less than 0.05 and F values more than 4 were defined as relevant parameters. A statistical significance was developed using ANOVA to draw the plots for responses of the present investigations. The mean differences between groups that are split on two factors are compared in a two-way ANOVA. Knowing the interaction between two independent variables and the dependent variables is the main goal of a two-way ANOVA. The two-way ANOVA is based on the ensuing presumptions.

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- The dependent variable is measured at continuous level.
- The variables should consist of groups based on the independent category.
- The observations should be independent, which implies there shouldn't be any relationships between the groups or within the same set of observations.
- The influence of the data points is not to be taken into account.
- For each combination of the groups of independent variables, the dependent variable must be normally distributed to it.
- Homogeneity of variances is required for each combination of the groups of independent variables.

4. Results and Discussion

4.1 Tensile strength

From the Table 3 lists the tensile strengths and moduli of the four, five, and six layered composite laminates made at each of the five different injection pressures. Figure 7 depicts the shattered portions of the randomly chosen specimen that was put under tension. Due to the separation of a significant number of fibers from the matrix, the failure was catastrophic and audible. The abrupt fracture denotes simultaneous matrix and fiber breakdown with total cracking. Figure 8 presents arbitrarily chosen load displacement curves for the current composites made at five chosen injection pressures. The corresponding 4, 5, and 6 layered composites at injection pressures P2, P3, and P4 had higher tensile strengths and moduli, thanks to superior matrix impregnation of the fiber, resin flow in the transition zone, and lower void content.

Table 3: Tensile properties of composites at preferred resin injection pressures

No of Layers	Injection pressure	Tensile strength(MPa)	Standard deviation	Young's modulus (GPa)	Standard deviation
	P1	71.900	4.12	1.451	0.29
	P2	104.160	3.49	2.536	0.10
Four	*P3*	103.950	2.31	1.856	0.27
	P4	83.500	4.47	1.682	0.34
	P5	81.410	3.41	1.583	0.27
	P1	86.620	2.16	1.594	0.13
	P2	112.480	4.15	1.883	0.43
Five	*P3*	126.810	4.23	2.637	0.24
	P4	119.500	2.38	2.417	0.27
	P5	113.300	3.94	2.253	0.27
	P1	136.840	4.25	2.197	0.56
	P2	143.580	3.73	2.293	0.65
Six	*P3*	144.070	4.33	2.456	0.20
	P4	153.060	4.79	2.716	0.26
	P5	136.700	4.01	2.031	0.20
	P5	136.700	4.01	2.031	0.20

Figure 7: Fractured parts of the specimen tested in tension

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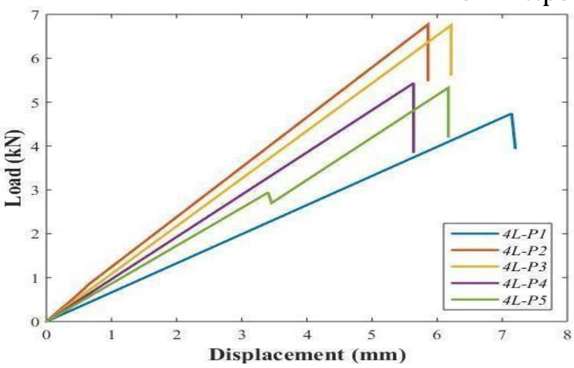
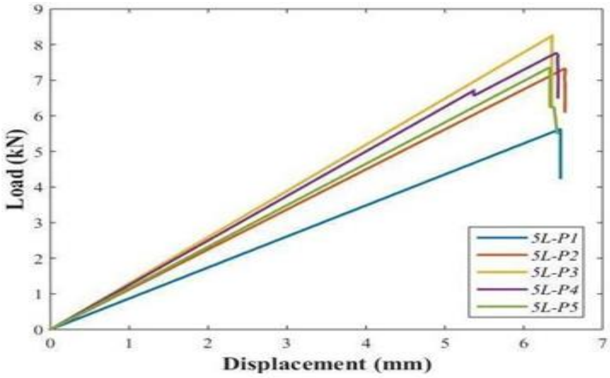


(a)



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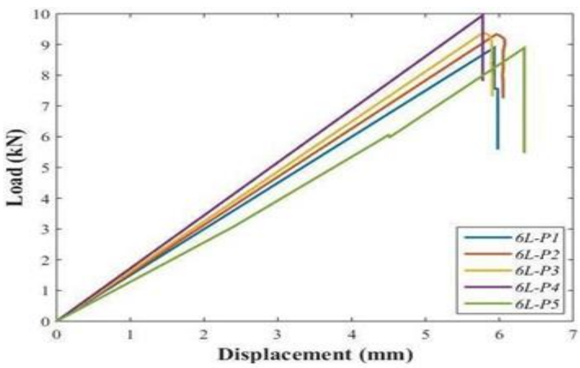

(c)

Figure 8: Load displacement curves for (a) 4, (b) 5 and (c) 6 layered composites at selected resin injection pressures.

Due to higher void content in the composites produced at injection pressures above P2, P3, and P4, the tensile strengths and modules are lower than those of other materials. This was proven by Figure 9, which depicts the fluctuation of tensile strength with respect to the resin injection pressure. Under the same injection pressure, composites' tensile strengths grew as fiber volume fraction did. Due to fewer voids and better fiber impregnation, the tensile strengths of 4, 5, and 6-layered composite sheets produced under varied injection pressures staken within the ideal values increased. Prior to ideal injection pressures, the strength of composites declined. This might be brought on by void expansion and fiber washout. As shown in Figure 3.20, for 4,5 and 6 layered composites, maximum tensile strengths of 104.16 MPa, 126.81 MPa, and 153.06 MPa were observed at their respective optimal injection pressures. At ideal pressures, the moduli of the identical composites were found to be 2.53 GPa, 2.63 GPa, and 2.71 GPa.

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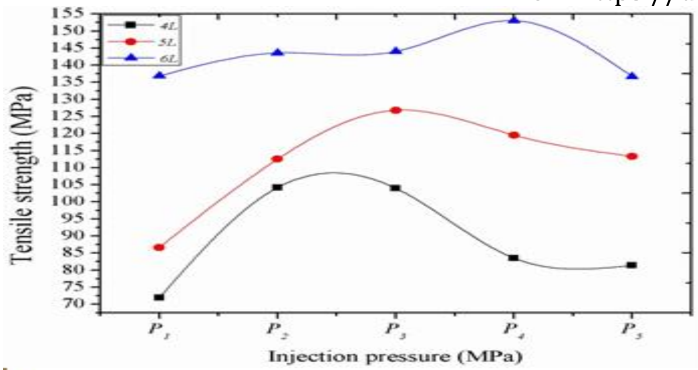


Figure 9: Variation of tensile strength with resin injection pressure

The tensile strengths and moduli of composites molded at corresponding ideal injection pressures are shown in Table 4 along with standard deviations. The acquired different load displacement graphs of the laminates treated at appropriate injection pressures are also shown in Figure 10. According to the results, at optimal injection pressure, 6 layered composite laminates had greater tensile strength and modulus than 4 and 5 layered composites. It was found that the modulus rose as the fiber volume fraction rose. The six-layered composite had a maximum tensile strength of 153.06 MPa, an ideal injection pressure of P4 (= 0.34 MPa), and a pregnancy velocity of 0.17 m/s. SEM photos of shattered surfaces of tensile test samples produced at optimal injection pressures are shown in Figure 11. The composites with modest fiber volume fractions contained higher debonds at various locations. The matrix and fiber have better adherence in six layered composites produced at pressure P4.This better adhesion may also result from the maximal strength provided by the six-layered composite material when it is molded at pressure P4.

Table 4: Tensile properties of composites at optimal resin injection pressures

No of layers	Optimal injection pressure (MPa)	Tensile strength(MPa)	Standard deviation	Young's modulus(GPa)	Standard deviation
Four	0.245	104.16	3.49	2.536	0.10
Five	0.294	126.81	4.23	2.637	0.24
Six	0.343	153.06	4.79	2.716	0.26

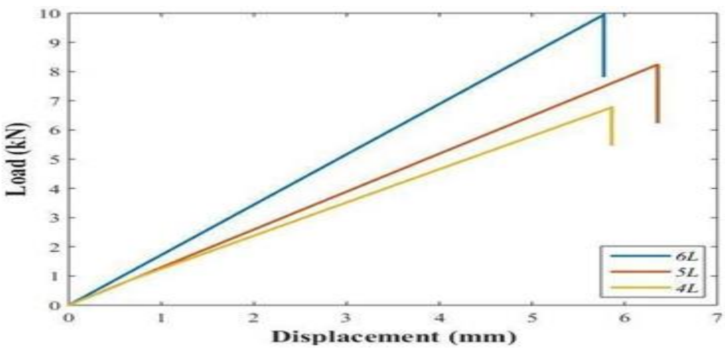
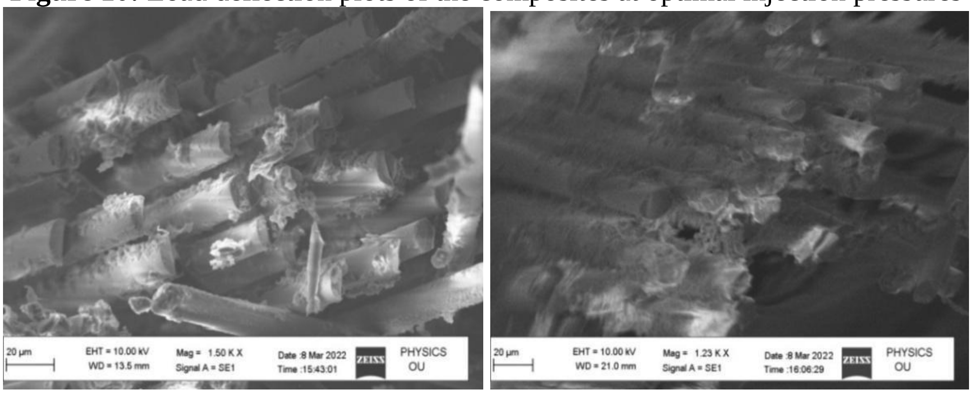
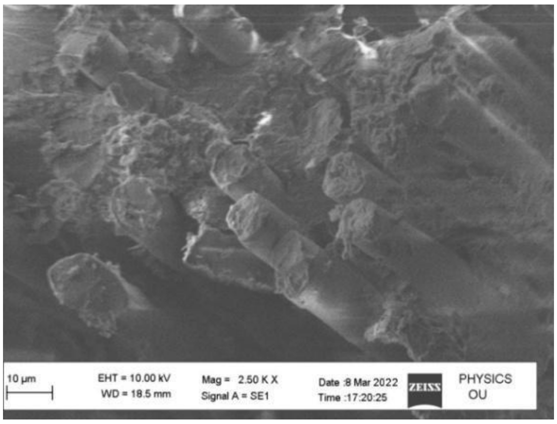


Figure 10: Load deflection plots of the composites at optimal injection pressures



(a) (b)



(c)

Figure 11: SEM images of samples tested in tension (a) four layers at P2 (b) five layers at P3and (c) six layers at P4

The quality of adhesion declined as the fiber volume fraction dropped. The surface of the chopped strand fiber withdrawal was clean and free of resin adhesion. As a result, the adhesion between matrix and fiber in the current composites is good. When a six-layered composite is treated at resin injection pressure P5, the matrix and fiber stick to the matrix more tightly. As the number of layers and pressure were reduced, the adhesion between the matrix and the fiber got worse. In comparison to other composites, the number of vacancies is considerably lower in six layered composites.

4.2 Variance Analysis for Responses to Effect on Tensile Strength

According to Table 5, the primary influencing parameter when compared to resin injection pressure is the number of layers. The tensile strength of the composite is 78.44% affected by the number of layers. Additionally, the resin injection pressure's contribution is 1.66%. The parameter P value of 0.005 in the current model shows that resin injection pressure is not a significant factor and that the number of layers in the composite is the important parameter.Themodelandthelinearsourceshavesignificanceontensilestrength.Model and linear respectively contributed 92.41% and 80.10%.

Table 5: Analysis of variance for tensile strength

Source	DF	Seq.SS	Adj SS	Adj MS	F-value	P-value	Contribution (%)
Model	5	8545.84	8545.84	1709.17	21.94	0.000	92.41
Linear	2	7407.73	7407.73	3703.86	47.54	0.000	80.10
L	1	7253.86	7253.86	7253.86	93.10	0.000	78.44
P	1	153.86	153.86	153.86	1.97	0.194	1.66
Square	2	1132.24	1132.24	566.12	7.27	0.013	12.24
*L**L*	1	58.10	58.10	58.10	0.75	0.410	0.6
*P *P*	1	1074.14	1074.14	1074.14	13.79	0.005	11.61
2-FI	1	5.88	5.88	5.88	0.08	0.790	0.06
*L**P*	1	5.88	5.88	5.88	0.08	0.790	0.06

5. Conclusions

With three different fiber volume fractions, the manufactured customized RTM was effectively used to create the chopped-strand GFRP composite laminates without any mold deformation, edge effect, or dry spot development. The central gating system has led to better impregnation of fiber. To determine the filling time without any visual obstructions, a flow visualization research was carried out. Mechanical testing was done on the composites to measure their impact, bending, and tensile strengths. The interplay between Reynolds number, void content, and mechanical properties was studied using an ANOVA. The findings of these investigations are summarized below.

The length of time it took for the resin to fill the preform layers increased. Front flow velocity was used to compute the Reynolds number, and the transitional and turbulent zones of resin flow patterns were clearly delineated. Based on resin flow pattern and the amount of voids present in moulded composites, the ideal injection pressure was recommended. In these composites, good fiber impregnation occurred. Superior tensile, flexural and impact strengths

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were obtained. At the ideal injection pressure, six-layered composites showed greater tensile, flexural, and impact strengths. The number of layers and resin injection pressure used during the creation of the composite has been shown to have a significant impact on the Reynolds number, void content, tensile, flexural, and impact strengths based on ANOVA.

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