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STUDY OF PERMEABILITY AND RESIN FLOW FRONT DURING THE FABRICATION OF THIN COMPOSITE USING VARTM PROCESS

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Abstract: The VARTM process is a liquid compaction Moulding process (LCM) which is most suitable for large components. The process consists of a transfer of liquid resin through reinforcing material loaded into a mold. During the resin infusion process, wetting of reinforcement characterized using the permeability properties. This study focused on the determination of the permeability of reinforcement used in composite manufacturing with visualization method. The flow front tracked during the infusion process. The permeability is determined using a tracked flow front. Permeability of the single reinforced fiber fabric is determined using visualization method. The data points obtained by tracking flow front with respect to time. This method applied to three different fibers fabrics of viz. Carbon, Glass, Aramid with different thickness. For the identical experimental condition, a simulation study also performed using ANSYS Fluent. In a transient simulation, the experimental permeability results were used as input for the flow front simulation. From the experimental and simulation approach, it was found that as the Permeability increases, the mold filling time decreased. From this study, it found that permeability depends on fiber architecture, porosity, and weight density of reinforcement material and resin viscosity.

Keywords: Permeability, Fiber Reinforced Composite, Resin Infusion, Flow Front, VARTM.

1. INTRODUCTION

In recent days, typical engineered composite materials are gaining attention due to its advantages over the metal and alloy materials (Florea and Carcea, 2012). The natural fiber-based composite, such as liquid wood is also getting attention due to its eco-friendliness and cost-effectiveness (Broitman et al., 2019). The selection of the composite fabrication process is playing an essential role based on product dimensions. The fabrication processes viz. manual layup, spray layup, autoclave process, Resin Transfer Moulding (RTM), and its advanced form Vacuum Assisted Resin Transfer Moulding (VARTM) etc. are used for fabrication of composite products. VARTM process is the variety of LCM which is most suitable for large components. The VARTM process has been extensively used in the last decades because it operates at ambient temperature, pressure, and is economical and accessible. The VARTM process offers many cost advantages over traditional RTM due to the low cost of the tooling, and Low injection pressure allows little movement of reinforcement during the VARTM process that leads to a better quality part. In this process, a vacuum pulls liquid resin in the form of a feed tube to distribute to the reinforcement. A flexible vacuum bag is placed over the top of the rigid mold using a sealant tape. The compaction of the preform occurred due to the differential pressure during the process. Schematic of the VARTM process shown in Figure 1 (Mazumder, 2002).

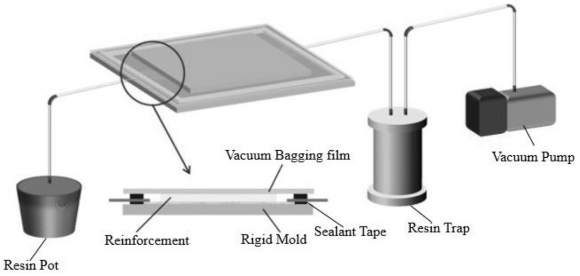

Fig. 1 Schematic of the VARTM process

Since the beginning of LCM, this process layout optimization conducted by trial and error, which resulted in high costs. More recently, with the development of mold filling simulation software, the process optimization can be done with the lower expense and higher accuracy. Indeed, this software allows prediction of resin flow front shapes, pressure and velocity fields, as well as mold filling time (Bruschke and Advani, 1993). However, complete material properties characterization is necessary to run those simulations accurately. One of the most critical properties to input in the software is Permeability (Šimáček and Advani, 2004).

The mold filling influenced by the permeability of the porous reinforcement material. It is an inherent property of the material, which includes all involvement with reinforcement and matrix. Permeability represents the flow through the porous medium. The complete prediction of the permeability tensor is crucial for understanding and forecasting the flow during the resin infusion from thick composite or the flow-through three-dimensional medium (Machado, 2016).

A vital issue in LCM processes requires the understanding of flow behavior inside the porous material. The permeability of a porous medium is a parameter, which denoted as the ease with which a fluid flows into the engineering textile material (Naik et al., 2014; Yun et al., 2017). Permeability is depended on many factors viz. the fiber structure, porosity, resin properties, processing conditions, the dimension of mold and part. (Kong et al., 2016; Kobayashi and Kitagawa, 2016).

Nedelcu and Carcea (2013) developed a mathematical model for layered composites using a metal matrix. The hydraulic pressure, reinforcement material, matrix type, fiber diameter, the mass ratio between the reinforcement and the composite masses and mold temperature were the vital parameters during the fabrication of layered composites.

Li et al., (2015) studied permeability of natural reinforced hybrid composites using the modified unidirectional Darcy's law.

Yuexin et al., (2008) studied the compression responses of glass fiber fabrics and carbon fiber fabrics with different layup designs and different kinds of materials in dry and wet compression tests. From their investigation, they found that permeability has significant importance to the preform and distribution media.

Nedelcu et al., (2010) studied fundamental experimental parameters for the stratified composite materials. They found that the interface between the reinforcement and matrix is the crucial aspect of composite fabrication.

Carlone and Palazzo (2015) used dielectric sensors to monitor mold filling and saturation. Sensors configuration was analyzed and improved with electromagnetic finite element simulations. A good agreement was found between unsaturated front positions provided by the considered system and acquired through conventional visual techniques.

Kim et al., (2018) has evaluated the permeability of three different types of glass fiber mats. They also reported interlaminar shear strength (ILSS) testing. They concluded that fiber architecture has an influence on permeability.

Raghu et al.,(2010) performed a simulation study under different infusion strategies and different process parameter. Injection flow with constant pressure was carried out to find the optimum location of the inlet and outlet port to improve the strength and quality of the product. The effect of process parameter such as injection pressure, permeability and resin viscosity on mold filling time was also studied. They simulated process for four different infusion strategies which had different inlet conditions. They also found that improper infusion strategy causes dry spot formations. The effect of mesh size was also played an essential role during the mold filling simulation process.

Woerdeman et al., (1995) reported an analytical approach to determine 3D permeability. The effective permeability acuried using permeability tensor which includes six highly non linear equations.

Weitzenbock et al.,(1998) recorded flow front using thermistors. They also described issues in measurement of 3D permeability due to capillary pressure.

Changchun et al.,(2015) developed a pressure sensor base device which can measure the permeability of the reinforcement material. Through thickness and in-plane permeability could be obtained using this device. They had compared the obtained result with the methods of camera recording and FBG sensors measuring.

In the present work, an attempt has been made to determine the permeability of the single-layer fiber reinforcement during the VARTM process using a visualization method for three different reinforcement material. The eccentric approach adopted to determine permeability without flow disturbance and racetracking. The determined permeability has been used as input for flow simulation. The mold filling time simulated for identical experimental conditions in ANSYS Fluent. The results of experiments and simulation have been compared with experimental results.

2. EXPERIMENTAL WORK

2.1 Material Selection

In present work, three types of reinforcement material and epoxy resin were used in the current work on permeability. The reinforcement used for composite manufacturing were Bidirectional (BD). The single layer of carbon, glass, and aramid fabrics was used as reinforcement materials. The properties of the reinforcement material were shown in Table 1.

Table 1. Properties of Reinforcement Material

	Carbon fiber	**Glass fiber**	**Aramid fiber**
Arial weight (g/m^2)	200	105	220
Density (g/cm^3)	1.8	2.62	1.4
Fiber diameter(µm)	7	7	12
Tensile strength (MPa)	4000	3100	3097
Tensile modulus (GPa)	240	80	105
Elongation (%)	1.7	4.8	2.8

2.2 Experimental Procedure

VARTM process setup was prepared to determine the permeability of single layer reinforcement materials. The dimension of the prepared mold was 150 ×400 mm. The rectilinear 1 D rectilinear method was used to determine the permeability during the VARTM process. The experiments were performed using liquid resin which consists viscosity of 278.8 mPa.s. The resin flows inside the porous preform with the help of pressure difference between inlet and outlet. The resin flow front was recorded using a camera which was fixed normal to the resin flow front. The time measurement was done using a stopwatch as shown in Figure 2.

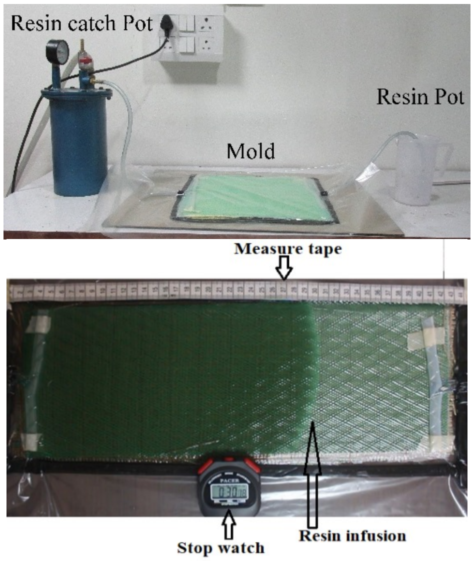

Fig. 2. VARTM setup

Permeability was measured using the Darcy law of flow through porous media given by equation (1).

$$\frac{K}{\phi} = \frac{\mu L^2}{2\Delta P t} \qquad (1)$$

where K is permeability, L is flow length in meter, t is a time in second, ϕ is porosity which equals to $1 - V_f$, where V_f is the fiber volume fraction, ΔP is a pressure difference between inlet and outlet. μ is the viscosity of the resin in Pa·s, was measured using a rotational viscometer.

3. RESULTS AND DISCUSSION

The resin flow front was tracked during the resin infusion process with respect to time. Based on the tracking of the flow front permeability was determined for single layer reinforcements. The flow simulation was carried out to validate the experimental mold filing time. The determined permeability was used as input of flow simulation.

3.1 Flow Front Tracking

It was observed that during entire resin infusion flow front remain constant. The constant flow front governs that neither fiber washing nor race tracking occurred. The resin flow visualization method allows the process defect free resin infusion process because there was no insertion of any foreign element inside the closed mold. Figure 3 represents the relationship between the square of front (L^2) flow positions with respect to flow time (t). Slopes of these plots were fitted using least square fit. The resin flow front was recorded during the resin infusion process under vacuum pressure. From the recorded flow front, the image frames were taken at regular interval of time. The distance of flow from inlet was measured using image processing. The Flow length was determined at a regular time interval, i.e. flow front position with respect to time. The data points were obtained through the flow front position. These data points were utilized to plot a graph between the square of flow length (L^2) vs time (t). The slope of this graph is used to calculate the permeability of reinforcement material.

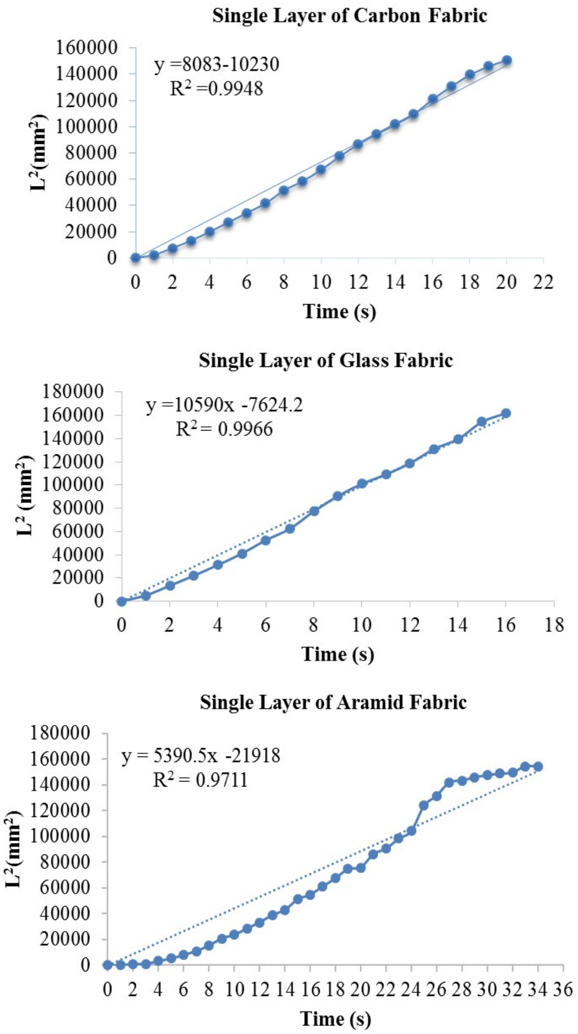

Fig. 3. Square of flow length vs time

The permeability of three types of reinforcements was calculated using data points achieved during the process as per the Figure 3. The equation (1) is the equation which governs Darcy's law used for permeability calculation. The calculated values of permeability are reported in Table 2.

Table 2. Results of permeability

Reinforcement	**Carbon**	**Glass**	**Aramid**
FVF	0.256	0.251	0.298
Porosity(Ø)	0.744	0.749	0.701
Slope (m^2/s)	8083	10590	5430
Flow Time (s)	20	16	34
Permeability ($\times 10^{-9}$ m^2)	8.25	0.10	5.22

The higher permeability was found for glass fiber fabric. As expected, as the higher Permeability results, the lower the mold filling time. The resin flowed more rapidly in glass fiber fabric than in Aramid fiber fabric because of the smaller flow channels. Due to less thickness of glass, reinforcement provides small macro channels for the resin flow. The filling time of a small macro channel is less compared to aramid reinforcement. The resin flow time for glass reinforcement was found shorter for the same infusion length.

3.2 Simulation of Resin Flow Front

The resin flow behaviour has been studied using a simulation model which was developed in the FLUENT package. The Interaction of porous reinforcement and the liquid matrix material is governing by Darcy's law and Volume of Fluid method (VOF). Through VOF, it is possible to identify the position of the interface among different phases of fluid during the process. The tracked flow front during the experimentation and image frame of the same time interval was captured from the transient simulation is shown in Figure 4. In simulation image frame saturated and unsaturated zone can be differentiated while in experiments, it cannot be observed by visual inspection.

It can be seen that the flow front profile is entirely rectilinear during the simulation process while in the experimental procedure, it is not perfectly rectilinear. It is due to leakage of vacuum and non-uniform material distribution (undulation) inside the mold. The non-uniform material distribution draws the resin flow faster towards vent in some region.

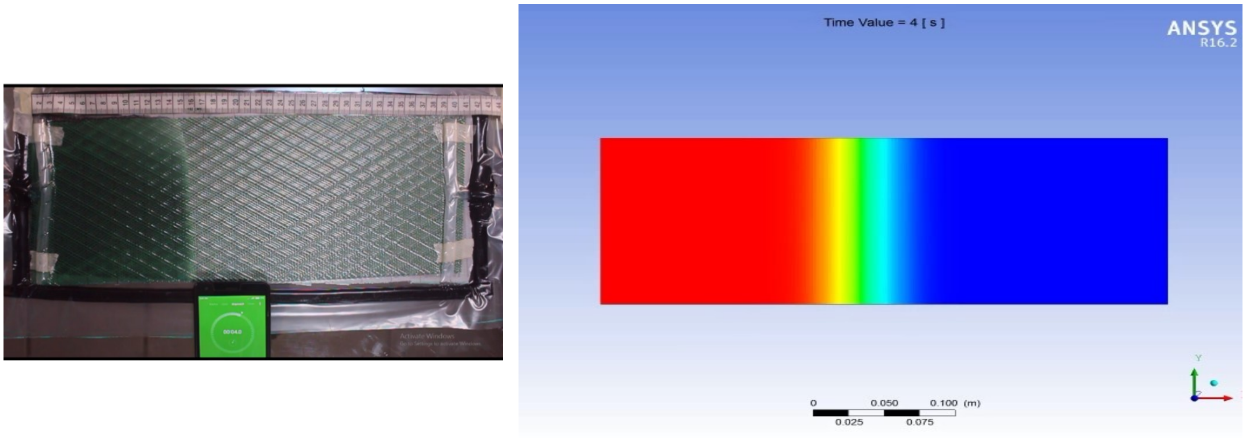

Fig. 4. Comparison of flow simulation and experiment with respect to time at 4 s

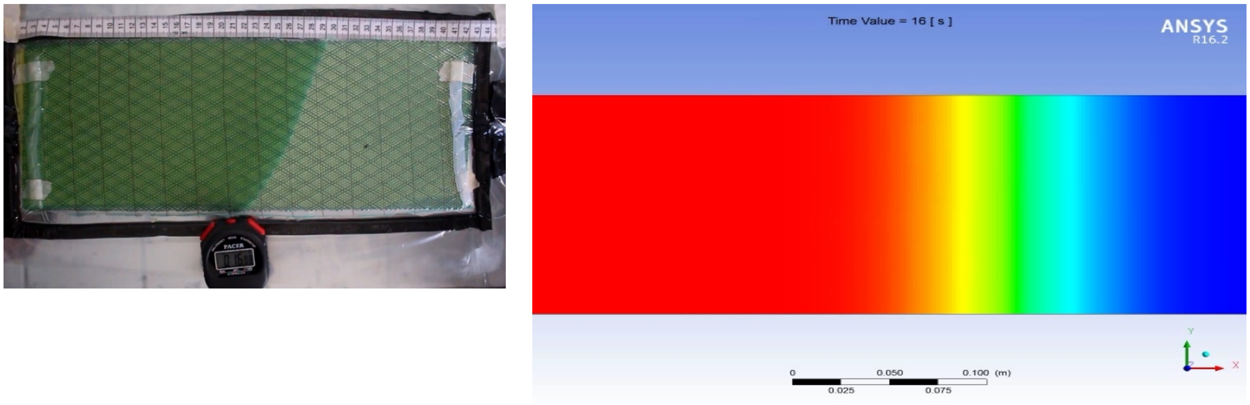

Fig. 5. Comparison of flow simulation and experiment with respect to at 16 s

The fiber Placement of reinforcement inside the mold plays an important role that affects the mold filling time and quality of composite. Imperfect placement of reinforcement at mold edges leads at the point to point variation during resin infusion. This small gap provides less resistance channel to flow of resin inside mold. The mold filling time was considered the time when the resin filled inside the mold. The comparison between experimental and simulated mold filling time is shown in Table 3 below.

Table 3 comparison of the mold filling time

Reinforcement	**Mold filling time by simulation (St)**	**Mold filling time by experiment (Et)**
Carbon	24	20
Glass	20	16
Aramid	42	34

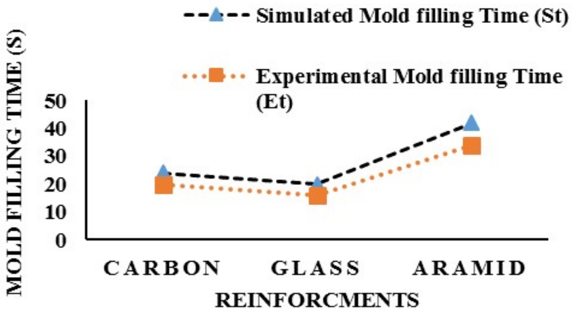

Fig. 6. comparison between experimental and simulated mold filling time

Figure 6 shows the comparison between experimental and simulated mold filling time for all three reinforcements. From figure it can be seen that experimental and simulation results are in good agreement.

5. CONCLUSION

In present work, single layer thin composite material was fabricated using a VARTM method using three different reinforcements. The permeability was determined using visualization method by tracking advancement resin flow front with respect to time. The resin flow simulation of the VARTM was carried out for identical experimental conditions. From the above study following conclusion are drawn:

1. For all three single layer reinforcements, the values of the permeability were determined by tracking resin flow fronts.
2. The higher permeability was found in glass fiber fabric. The experimental mold filling time of single-layer glass fabric was 16s which was the lowest among all three reinforcements. Due to lower thickness of glass fiber fabric, it consist of small macropores compare to other reinforcements. The filling of small macropores fills faster than larger pores which leads to faster mold filling.
3. The lowest permeability was found in aramid fiber fabric.it can also be observed that fiber architecture of the reinforcement plays a vital role during the resin infusion. The fine fiber architecture of the aramid reinforcement offers more resistance do resin during the infusion. The highest experimental mold filling time was observed, i.e. 34 s due aramid reinforcement having fine and large number macro pores compared to glass and carbon reinforcements.
4. From the results of experimental and simulation study, it was found the good agreement can be observed in mold filling time. The Flow front simulation is a useful tool to minimize the trial and error approach in the VARTM process.
5. In a VARTM process, the parameters such as resin viscosity, reinforcement thickness, vacuum pressure, porosity and fiber architecture strongly affect the mold filling time.

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