

Thermoplastic Resin Flow Behaviour in Foam Core Sandwich Composites for Aerospace Applications During Vacuum Infusion Process

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This article presents the research findings on the flow behaviour of thermoplastic resin in foam core sandwich composites for aerospace applications during the vacuum assisted infusion process. After optimizing the process parameters, two sandwich panels were manufactured using glass fibre fabrics, a polymethacrylimide (PMI) foam core, and a liquid acrylic resin. To compare the sandwich and monolithic structure process behaviour, a monolithic composite panel was also manufactured. By combining experimental monitoring with Darcy's law, permeability differences between the structures were evaluated. The results indicate that PMI foam does not significantly affect the resin flow trend, and that Darcy's law can be applied to both monolithic and sandwich structures when a thermoplastic liquid resin is used. These findings offer theoretical guidance for process parameter design and real-time in situ monitoring of the vacuum infusion process.

Keywords: Thermoplastic Composites, Sandwich Structure, Vacuum Infusion, Darcy's Law, Aerospace Applications.

1 Introduction

In recent years, fibre reinforced thermoplastic composites have attracted increasing interest as structural materials, offering low weight combined with high strength, along with reduced handling constraints, improved health and safety characteristics, and the possibility of welding and recycling, advantages not typically associated with traditional thermoset systems. In particular, sandwich composites tend to be key components in aerospace applications such as radomes for aircraft or radar antennas due to their high designability, specific bending stiffness and strength. Applying the advantages of the mechanical properties and ecological aspects to large scale sandwich structures while avoiding the problems of high production costs is the main goal of current research. As the vacuum infusion process allows cost effective manufacturing of large and geometrically complex components, it meets all requirements. [1–3]

Vacuum assisted resin infusion (VARI) under flexible membrane (vacuum bag film) is a highly flexible method used for both small and large complex structures. A liquid system is infused into continuous fibre reinforcement, thereby impregnating it. After the resin infusion is complete, the composite is cured at room or elevated temperature depending on the polymer matrix used. The production of composites with a thermoplastic matrix by infusion technologies is feasible using in situ polymerization when the

system has a sufficiently low viscosity. A suitable monomer mixed with the initiator is infused through a plane into the reinforcement enclosed between the bottom mould and the top flexible membrane under vacuum. By eliminating the top mould and requiring only technological layers instead, plus being able to work at room temperature, this method is cheaper than any other. [4, 5]

Polymer based composites represent a broad class of materials in which the selection of the matrix and its physicochemical characteristics influence processability, particularly during impregnation and infusion steps. Considering key material parameters such as viscosity, moisture absorption, processing temperature, process window, service temperature, mechanical properties, availability, and cost, acrylic polymers appear to be the most suitable choice for this study. Acrylic polymers are amorphous linear thermoplastics that can be processed via radical polymerization at or near room temperature, with dynamic viscosity above 0.1 Pa·s. Acrylic resins may contain methacrylate monomers such as methyl methacrylate or butyl methacrylate, as well as acrylate copolymer chains. The reaction takes place in the presence of a thermal initiator. The variability of the available resins consists in copolymerization; for example, vinyl acetate can be added to acrylate monomers as a comonomer to modify and improve the mechanical properties of the polymer. [1, 5–7]

This paper is focused on the study of thermoplastic resin flow in sandwich structures, the application and

experimental validation of Darcy's law using the vacuum infusion process, and a comparison of the results with a monolithic laminate. Predicting the behaviour of various thermoplastic composite structures could help prevent manufacturing issues and make thermoplastic materials competitive with thermosets, especially because of their favourable environmental and health aspects.

2 Theory and Formulation

The flow behaviour of the thermoplastic resin through the reinforcement during the vacuum infusion process can be characterized using permeability properties. Permeability indicates the relative ease with which the resin passes through the pore space in the porous medium, and it depends on reinforcement architecture, porosity, resin properties, processing conditions, mould design and part geometry. The resin properties affecting permeability are viscosity, surface tension and contact angle. Processing conditions such as infusion pressure, flow rate and temperature also affect permeability. The reinforcement permeability is one of the most critical properties closely related to processing time and porosity in the final composite part. [8, 9]

There are many studies on determining the permeability of different fibre reinforcements. Permeability is a directional quantity that varies in three dimensions within the preform, but the transverse permeability is not used in most cases as manufactured components are usually thin enough to neglect this dimension. The possibility of neglecting transverse permeability in sandwich panels will be verified in this study.

The simplest characterization technique is to make unidirectional flow measurements in each major direction. Typically, the configuration consists of a rectangular mould with the infusion inlet placed on one side and vacuum outlet applied on the opposite side. To obtain permeability values, the flow rate of the resin is measured throughout time. In this study, the two main permeabilities are considered as equal,

so only unidirectional permeability measurements were performed for each laminate. From the unidirectional expression of Darcy's law (1), the following relation can be obtained by integration in time:

$$K = -\frac{x^2 \mu \Phi}{2 \Delta p t} \quad (1)$$

Where:

K... Permeability [m²],

x... Flow front position [m],

t... Infusion time [s],

μ ... Dynamic viscosity [Pa·s],

Φ ... Porosity of reinforcement,

Δp ... Pressure difference between infusion pressure and ambient pressure [Pa].

The porosity of reinforcement Φ can be obtained as $\Phi = 1 - V_f$, where V_f is the fibre volume fraction that can be calculated by using the following equation:

$$V_f = \frac{W_f}{\rho_f CPT \cdot 1000} \quad (2)$$

Where:

W_f ... Fibre area weight of each ply [g/m²],

ρ_f ... Density of the reinforcement [g/cm³],

CPT... Cured ply thickness [mm]. [10–12]

3 Experiment Setup

3.1 Materials

Two sandwich structures with dimensions of 650×350 mm composed of two glass fabric skins (US Style 7781, Interglas 92626, 296 g/m²), each skin consists of four layers oriented 0/90°, and a PMI foam core (ROHACELL® 71 HF, thickness 6 mm) were produced sequentially on different days to verify the repeatability of the process. A monolithic panel intended for comparison has layers also oriented [0/90]⁴ and same dimensions as sandwiches. A representation of such monolithic and sandwich lay-up can be seen in Figure 1 below.

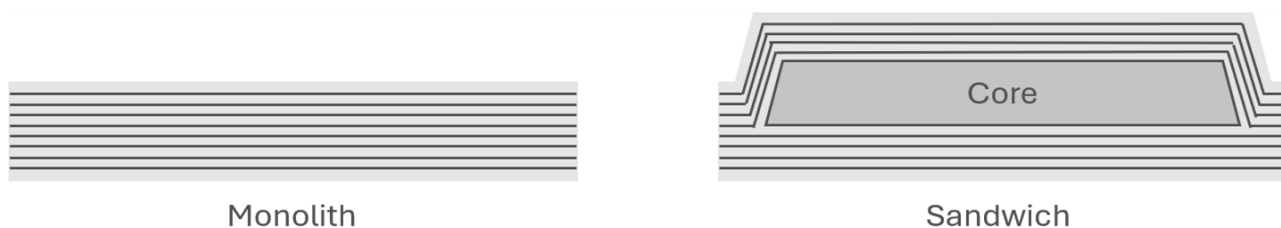


Fig. 1 Monolithic vs sandwich composite lay-up

Both types of structures were impregnated with acrylic resin ELIUM®188 XO from the manufacturer ARKEMA. NOVIPER BP 50, containing 50 % active dibenzoyl peroxide, was used as the initiator of the radical polymerization at 3 phr (3 wt. % relative to the

resin), as recommended by the manufacturer's technical data sheet. The monomer methyl methacrylate (MMA) converts to polymer polymethyl methacrylate (PMMA) using peroxide initiator at room temperature, see Figure 2.

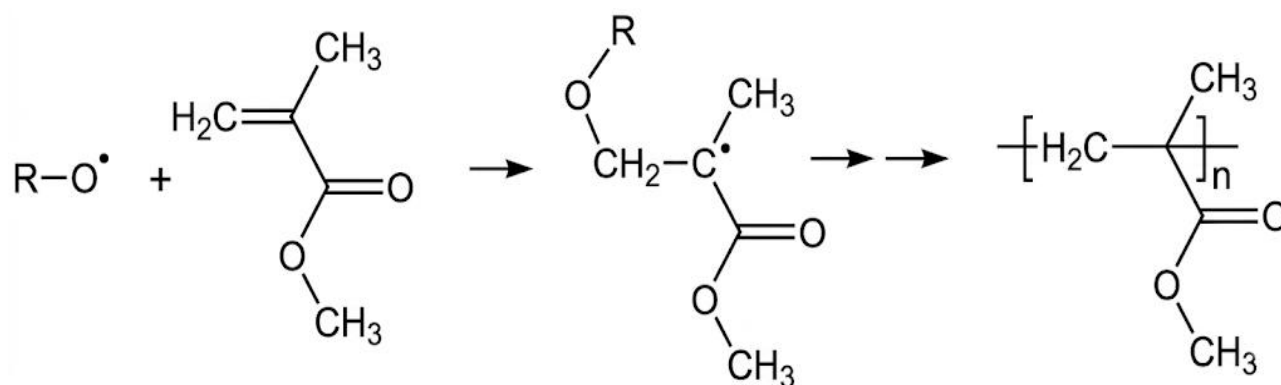


Fig. 2 Radical polymerization of MMA monomer to PMMA polymer [13]

3.2 Vacuum Assisted Resin Infusion

After the process parameters were sufficiently optimized to ensure high-quality impregnation of the fabric and homogeneity of research results, the composite panels were manufactured by the VARI process while manually monitoring and recording the resin flow.

The technological layers included peel ply, flow distribution medium, vacuum bag film, sealant tape, resin inlet and vacuum outlet hoses, etc. Individual layers of reinforcement were stacked on top of each other to form a laminate of the specific configuration. The bottom Al alloy tool was cleaned and treated with base wax and Polivaks™ EKO PVA liquid release agent so that the composite panel could be properly removed from the tool after curing without any damage.

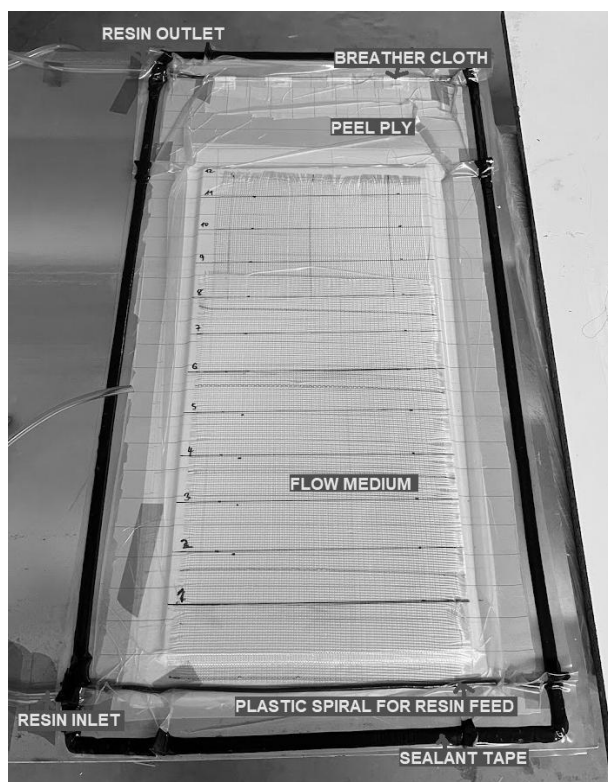


Fig. 3 Vacuum assisted resin infusion set-up

After placing all the reinforcement on the separator-treated tool, the peel ply layer was placed on its entire surface of the fabric and extended on the vacuum side so that it reaches the breather cloth. A 100-mm span of peel ply leading up to the breather cloth vacuum outlet acted as the “resin-brake” which prevented the resin from entering the vacuum tube. The flow distribution medium was laid on the fabric at a length of 50 mm before its end. Finally, the plastic spirals for the resin feed were arranged, along with the inlet and outlet hoses, and a vacuum bag film covered the whole area sealed with the sealing tape. How the entire set up was bagged is shown in Figure 3.

After the setup was completed, the resin inlet was clamped, and the hose from the vacuum pump was connected to the outlet of the device via a pressure vessel. The vacuum level was set to -0.6 bar. Then, after switching off the pump, a leak test was performed for at least 10 minutes to check the feasibility of the factory setting and to ensure that there were no leaks that could later create voids in the cured laminate.

Once the entire assembly was ready to be infused, the next step was to prepare the resin. ELIUM®188 XO resin and initiator were properly mixed, but it wasn't degassed based on previous experiments. The results didn't show significant differences between degassed and non-degassed composites. After mixing, the resin was allowed to stand for 25 minutes before starting the infusion to sufficiently homogenize the resin and remove gas bubbles by rising to the surface. Then the resin was infused, and the flow front was marked and recorded. Impregnation was performed at room temperature ranging from 20 to 25 °C. The curing conditions consisted of two steps, the first at room temperature for 24 hours, the second at 80 °C for 2 hours, to provide the declared properties of the polymer matrix for the eventual use of composite panels. The monolithic composite panel was bagged, infused and cured under the same conditions as the sandwich panels.

3.3 Resin Flow Monitoring

During the experiment, a high-speed digital camera (60 fps) was used to record the exact moment when the resin flow front reached each marked position on the composite specimen. The individual positions were 50 mm apart, measured using a metal ruler, and the resin was introduced from a single inlet and distributed across the full width of the reinforcement using a plastic spiral to ensure uniform resin flow. Impregnation was conducted at room temperature

(20–25 °C), and the resin viscosity was approximately 100 mPa·s, as specified by the manufacturer. The experiments were repeated for both sandwich and monolithic structures; for sandwiches, two identical specimens were produced to ensure reproducibility. The following Figure 4 shows the marked positions on the vacuum bag film and the resulting cured sandwich composite panel, which may be used for subsequent complementary tests and material analyses if needed.

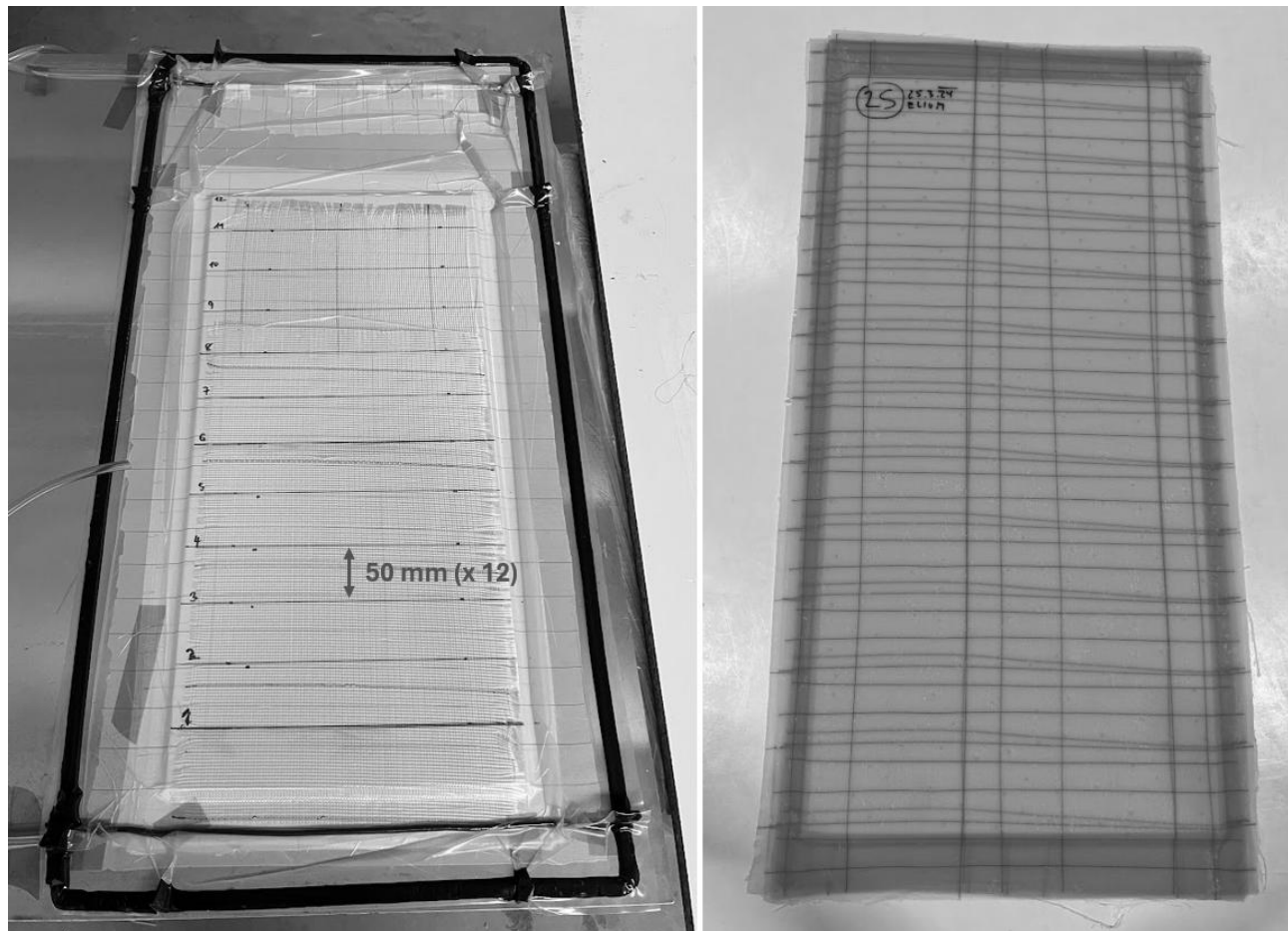


Fig. 4 Positions marked on the vacuum bag film to record the resin flow front and final cured sandwich composite

4 Results and Discussion

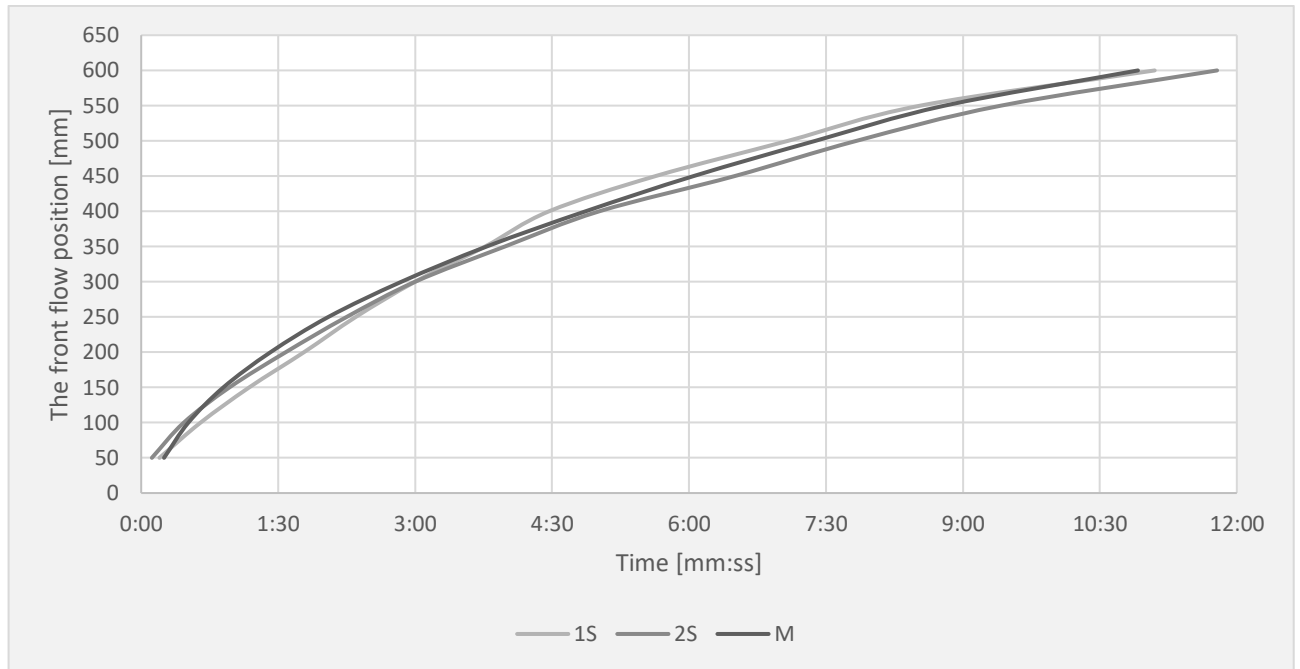
The resin flow during the infusion was monitored at marked positions along the specimens, spaced 50 mm apart, which corresponds to the scale used in the following graphs. Two identical sandwich panels (1S and 2S) were produced to ensure reproducibility, and one monolithic panel (M) was also monitored for comparison. The recorded video frames were manually analysed to determine the flow front position over time. All data were processed using Microsoft Excel to calculate the resin flow rates, and the permeability was calculated by substituting the recorded data into Equations (1) and (2). These results provide the basis for comparing the flow

behaviour of sandwich and monolithic structures.

5 Experimental Data

5.1 Resin Flow Position in Time

The specific time recorded at a given resin flow front position can be very useful in predicting the resin flow behaviour in other manufactured parts. Therefore, it is also necessary to focus on these parameters for this relatively newly used thermoplastic PMMA resin. As can be seen in Graph 1, the result is a dependence of the resin flow front position on time, meaning we can tell how long it will take for the resin to flow a certain length through the reinforcement from the start of infusion.

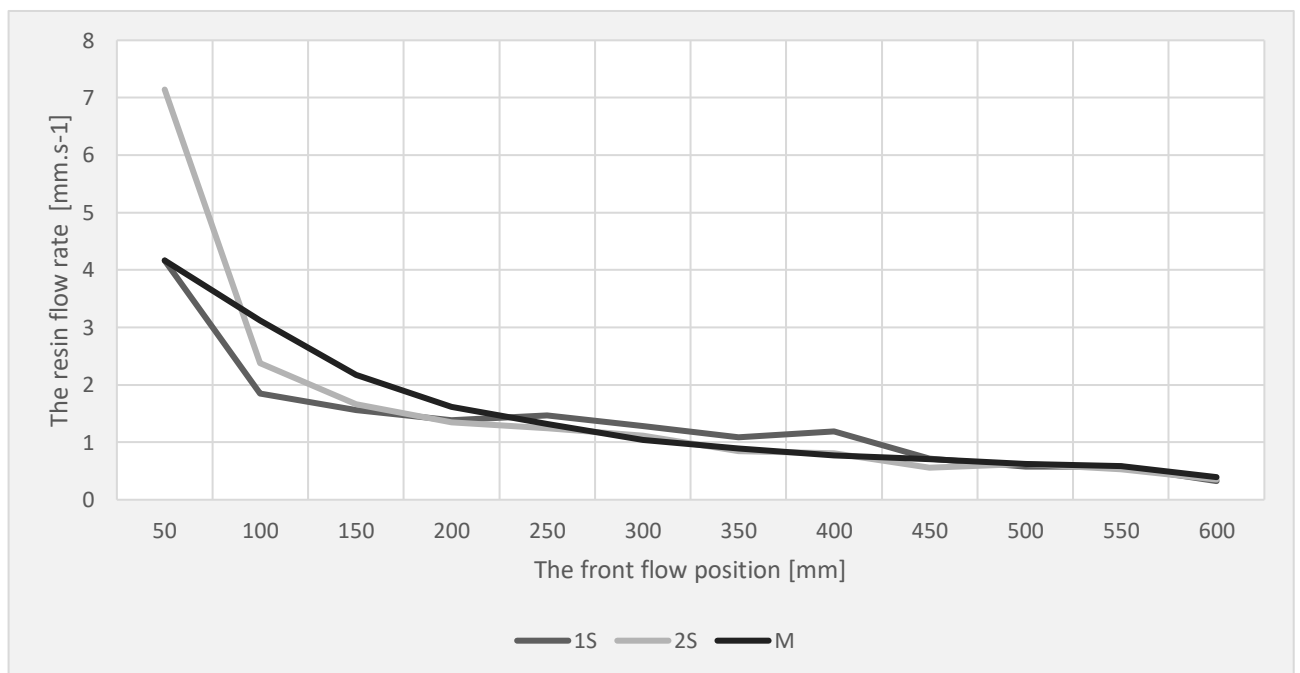


Graph 1 Resin flow front position in time for sandwich (S) and monolithic (M) structures

From the curves of the graph above, it can be read that the resin flowed through the reinforcement of the first two sandwich specimens 1S and 2S at approximately the same time. If we compare the curves of the sandwiches (S) with the monolithic one (M), we can see that the resin in the monolithic specimen flowed through the reinforcement approximately as fast as in the sandwiches, because they have same number of fabrics plies oriented 0/90. Thus, the 6mm PMI foam core did not play a role in the processing time.

5.2 Resin Flow Rate

By using the resin flow rate at a given position on the composite plate, we can also improve the prediction and overall behaviour of the resin. It is necessary to know in which areas of reinforcement the resin flow is faster, or where it slows down and it is necessary to consider the increasing viscosity of the thermoplastic resin. The resin flow rate at a given position for both sandwich and monolith structures can be seen in the graphical representation in Graph 2 below.



Graph 2 Resin flow rate at a given position for sandwich (S) and monolithic (M) structures

From all curves of the resin flow rate shown above, it can be said that right from the start of the infusion, the resin flow is noticeably faster, and its rate decreases with greater distance from the beginning of the reinforcement, meaning the flow is slower as the area of the impregnated reinforcement and the viscosity of the resin increase.

6 Permeability Calculation and Analysis

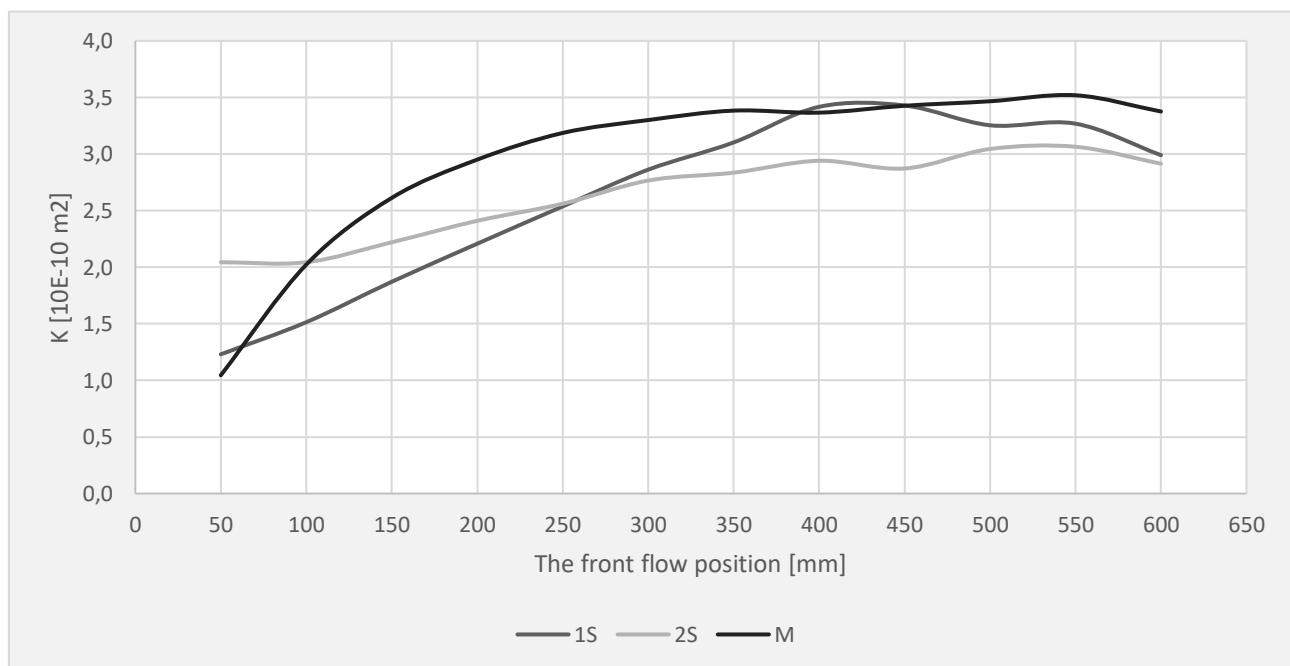
The permeability K was obtained by applying Eq. (1) at different positions in the process. The fibre volume fraction required for the permeability

calculation can be easily obtained when the fibre area weight of each ply, the density of reinforcement and the cured ply thickness is known. The resulting values of both sandwich (1S, 2S) and monolith (M) structures are summarized in Table 1, including the mean value (Mean) and the standard deviation (SD) calculated for the sandwich structures.

In Graph 3 hereafter, there is a graphical representation of the dependence of permeability on the resin flow front position in the reinforcement that could be used to identify in which areas more or less resin easily passes through the reinforcement.

Tab. 1 Results of permeability K (10^{-10} m^2) and fibre volume fraction V_f for sandwich (1S, 2S) and monolithic (M) structures

Position [mm]	K (10^{-10} m^2)					V_f				
	1S	2S	Mean	SD	M	1S	2S	Mean	SD	M
(1) 50	1.2303	2.0443	1.6373	0.5756	1.0451	0.5179	0.5327	0.5253	0.0105	0.4881
(2) 100	1.5142	2.0443	1.7792	0.3748	2.0228	0.5179	0.5327	0.5253	0.0105	0.4881
(3) 150	1.8714	2.2205	2.0460	0.2469	2.6128	0.5179	0.5327	0.5253	0.0105	0.4881
(4) 200	2.2076	2.4101	2.3088	0.1432	2.9509	0.5179	0.5327	0.5253	0.0105	0.4881
(5) 250	2.5372	2.5611	2.5492	0.0169	3.1863	0.5327	0.5484	0.5406	0.0111	0.4881
(6) 300	2.8620	2.7660	2.8140	0.0679	3.3004	0.5327	0.5484	0.5406	0.0111	0.4881
(7) 350	3.1026	2.8355	2.9690	0.1889	3.3840	0.5327	0.5484	0.5406	0.0111	0.4881
(8) 400	3.4173	2.9406	3.1790	0.3371	3.3659	0.5327	0.5484	0.5406	0.0111	0.4985
(9) 450	3.4293	2.8724	3.1509	0.3938	3.4268	0.5327	0.5484	0.5406	0.0111	0.4985
(10) 500	3.2542	3.0447	3.1494	0.1481	3.4666	0.5484	0.5327	0.5406	0.0111	0.4985
(11) 550	3.2685	3.0646	3.1665	0.1441	3.5193	0.5484	0.5327	0.5406	0.0111	0.4985
(12) 600	2.9903	2.9146	2.9525	0.0535	3.3762	0.5484	0.5327	0.5406	0.0111	0.4985



Graph 3 Permeability K (10^{-10} m^2) for sandwich (S) and monolithic (M) structures

From the graphical representation above, the individual curves are generally consistent with the trends observed in the previous graphs. For both

sandwich (1S, 2S) and monolithic (M) specimens, the permeability of the reinforcement was found to increase along the length of the sample, i.e., K values

are lower at the resin inlet than at the outlet. It should be noted that Darcy's law assumes a constant resin viscosity. In reactive resin systems, viscosity may increase during polymerization. However, in the present experiments, resin flow was completed within a time frame much shorter than the onset of viscosity growth, which typically begins around 60 minutes after mixing the resin with the initiator [14]. Therefore, the effect of increasing viscosity on the measured resin flow and calculated permeability is considered as negligible.

The permeability values for the two sandwich panels were consistent, with standard deviations ranging from 0.0169 to $0.5756 \times 10^{-10} \text{ m}^2$, indicating that the experiment produced reliable and reproducible results. Minor differences between the sandwich and monolithic panels are evident, which can be attributed primarily to experimental variability, such as slight differences in fibre volume fraction and local reinforcement compaction, rather than the presence of the PMI foam core. These findings highlight that the PMI foam does not significantly impede resin flow under the tested conditions. The observed trends are conceptually consistent with previous studies on conventional epoxy matrices in the VARI process [10, 11, 15], which reported that flow in fibrous reinforcements under vacuum infusion exhibits similar behaviour and can be described using Darcy's law.

7 Conclusion

In this study, the resin flow behaviour of a liquid acrylic thermoplastic system was experimentally investigated in both foam core sandwich and monolithic glass fibre composites using the VARI process. Monitoring the resin flow front position and rate over time, combined with application of Darcy's law, enabled quantification of in-plane permeability in each configuration. The manufacturing of two sandwich specimens and one monolithic specimen proved that the presence of a 6mm thick PMI foam core did not alter the resin flow trend. It means that infusion times, flow front rates, and permeability values were statistically equivalent between sandwich and monolithic laminates with identical fabric lay-up. All specimens exhibited a gradual increase in permeability along the flow path, confirming that Darcy's law remains valid for thermoplastic systems in both structural types.

These results demonstrate that thermoplastic resin infusion into foam core sandwich composites can be reliably predicted using classical porous media flow theory. The negligible influence of the foam core on permeability simplifies process design and permits use of identical infusion parameters for both sandwich and monolithic composites. Overall, this work

provides a theoretical basis for the efficient manufacturing of large-scale thermoplastic sandwich structures in the aerospace industry.

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