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EFFECT OF PROCESS VARIABLES ON THE PERFORMANCE OF GLASS FIBRE REINFORCED COMPOSITES MADE BY HIGH PRESSURE RESIN TRANSFER MOULDING

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Abstract

The CAFE regulations will require average fuel consumption of cars and light duty trucks to be reduced from 27 mpg to 54.5 mpg by 2025. In order to reach this requirement, automakers have to improve both the vehicle powertrain efficiency and the vehicle weight. Polymer composite materials are a preferred alternative to achieve the needed weight reduction by combining a higher strength to weight ratio than steel and aluminum, superior fatigue and corrosion resistance than metal and very good crashworthiness characteristics. However, high throughput and cost effective composite manufacturing processes are essential for high performance fibre reinforced polymer composites to penetrate the automotive market to their full potential. High Pressure Resin Transfer Moulding (HP-RTM) process is a new process based on the Resin Transfer Moulding (RTM) technology that enables the processing of very reactive resins in very short cycle times (< 5-10 min i.e. >25,000 parts per year) with various types of reinforcement (glass, carbon, natural fibre). With HP-RTM's unique self-cleaning impingement mixhead, resins that react in less than 1 minute (fast-curing epoxy or polyurethane systems) can still be processed. This process, combining the high mechanical performance of RTM parts with short cure cycle, thus presents a great interest for automotive applications. In this study, the effect of the process parameters, such as the injection flow rate, the vacuum assistance sequence and mould gap control, on the mechanical performance and quality of HP-RTM composite plates was determined and HP-RTM process mapping was established from the obtained mechanical results.

Introduction

According to the new CAFE (Corporate Average Fuel Economy) regulation, fuel consumption of all cars and light duty trucks should increase from 27 miles per gallon (mpg) to 54.5 mpg by 2025. To reach this requirement, vehicle powertrain efficiency and vehicle weight have to be improved. Polymer composite appear to be one of the best alternative to achieve the needed weight reduction by combining a higher strength to weight ratio than steel and aluminum (50-70% weight reduction as a replacement of steel with carbon fibre and 25-35% with glass fibre), superior fatigue and corrosion resistance than metal and very good crashworthiness characteristics, as well as possibility for complex shapes structures with fewer sub-components, thus reducing assembly time and cost.

In the past decades, liquid injection moulding processes have been widely used to manufacture high performance composite structures in marine and automotive applications.

In this study, glass fibre reinforced composites were made by HP-RTM using a fast-curing epoxy resin system. The effect of the process parameters, such as the injection flow rate, the vacuum assistance sequence, mould gap control and binder concentration, on the mechanical performance and quality of HP-RTM composite plates was determined and HP-RTM process mapping was established from the obtained mechanical results.

Experimental

Materials

VORAFORCE™ fast-cure epoxy resin system from Dow was used as thermoset matrix. This resin system was especially developed for fast injection process. Prior to processing experiments, the chemical and rheological behaviours of the resin system were characterized using a Differential Scanning Calorimeter (DSC, Q2000 system from TA Instruments) and a parallel plate geometry rheometer (ARES system from Rheometric Scientific), respectively. Figure 1 shows the resin reactivity at 100 °C which correspond to the typical curing temperature. The resin reaches its gel time in 50 to 60 seconds and fully cures in less than 250 seconds (approx. 4 minutes). Also it can be noticed that the resin reaches a viscosity superior to 1 Pa.s after 40 seconds. From a manufacturing point of view, this implies that the mould filling and impregnation of the reinforcement should be done in less than 40 seconds, in the resin processability region.

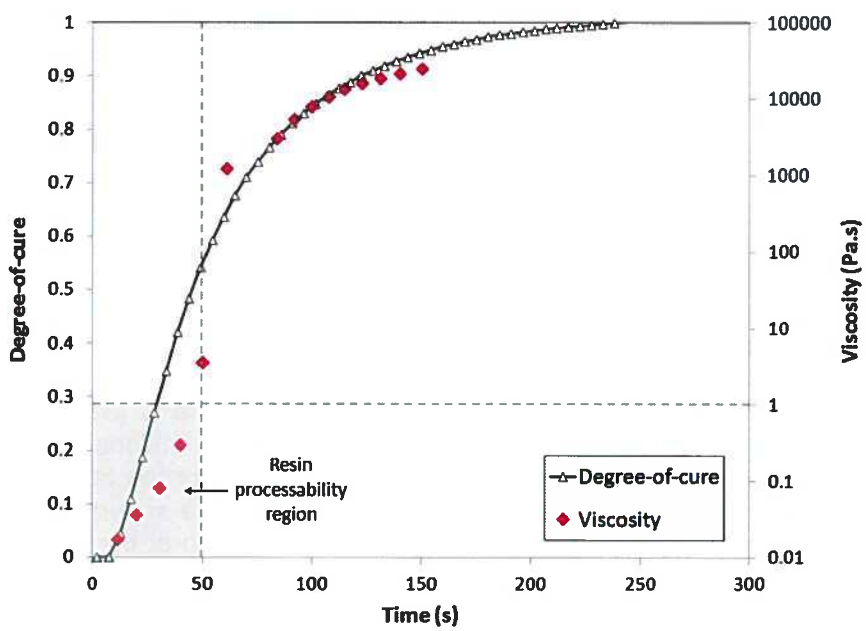

Figure 1: Variation of the degree-of-cure and the viscosity of the VORAFORCE™ epoxy at 100 °C

Dry quadraxial [0°/-45°/90°/45°] glass non-crimp fabric with an areal weight of 1205 g/m^2 was used as reinforcement. In order to limit fiber wash-out and fibre displacement, an epoxy-based binder was applied to the glass fiber fabric. Different binder concentrations (0%, 4%, 5% and 6%) were applied on one or both surfaces of the fabric.

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Fibre volume fraction and porosity

Following ASTM standard D2584 [19], sample pyrolysis was carried out to determine the sample fibre volume fraction and the void content. The sample was maintained in the oven for 2 hours at 600 °C. Up to nine samples per plaque from different location were burned.

Results

For all the tested conditions, no gradient in properties was observed between the samples taken from the top, middle or bottom of the panel. Therefore, in the following, only the results from the samples located in the middle of the panel will be presented.

Injection HP-RTM

Fibre alignment

Prior testing, an observation of the tensile sample showed fibre misalignment in certain cases. The fibre misalignment was characterized by the ratio of deviation length over the sample width. The fibre deviation was then plotted versus the resin injection rate, as shown in Figure 2. A large fibre misalignment was observed for fabric with no binder, especially with high flow rate. Binder help to reduce the fibre displacement, however, misalignment up to 45% were still observed for high flow rate (85 g/s). The fibre misalignment seems independent of the binder concentration and location, but flow rate dependant.

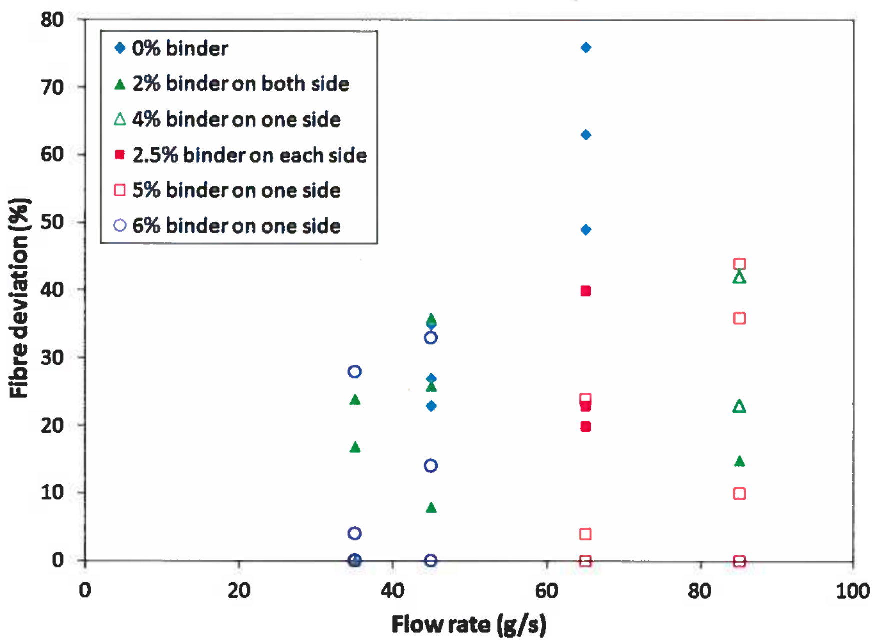


Figure 2: Tensile sample fibre deviation with resin injection rate for injection HP-RTM process

Tensile tests

Figure 3 shows the tensile modulus and tensile strength of glass/epoxy composite panels manufactured by injection HP-RTM under various conditions. The varied process parameters were the resin injection rate from 35 g/s to 85 g/s, the binder content and the vacuum sequence

[TM] Trademark of The Dow Chemical Company ("Dow") or an affiliated company of Dow the flexural properties of composite panels made without vacuum assistance while the properties of the panel made by applying vacuum until the end of the impregnation are plotted in Figure 4-c and Figure 4-d.

As for the tensile properties, the binder concentration is the parameter that affects the mechanical properties the most. A decrease of 20% and 30% in flexural modulus is observed from 4% binder concentration for panels made without vacuum and with vacuum assistance, respectively. A significant decrease in flexural strength, up to 50%, is also observed above 4% binder concentration for the panel made with vacuum. The resin injection rate does not affect the flexural properties, except at 0% binder. In that case, a lower injection rate induces higher flexural modulus and flexural strength.

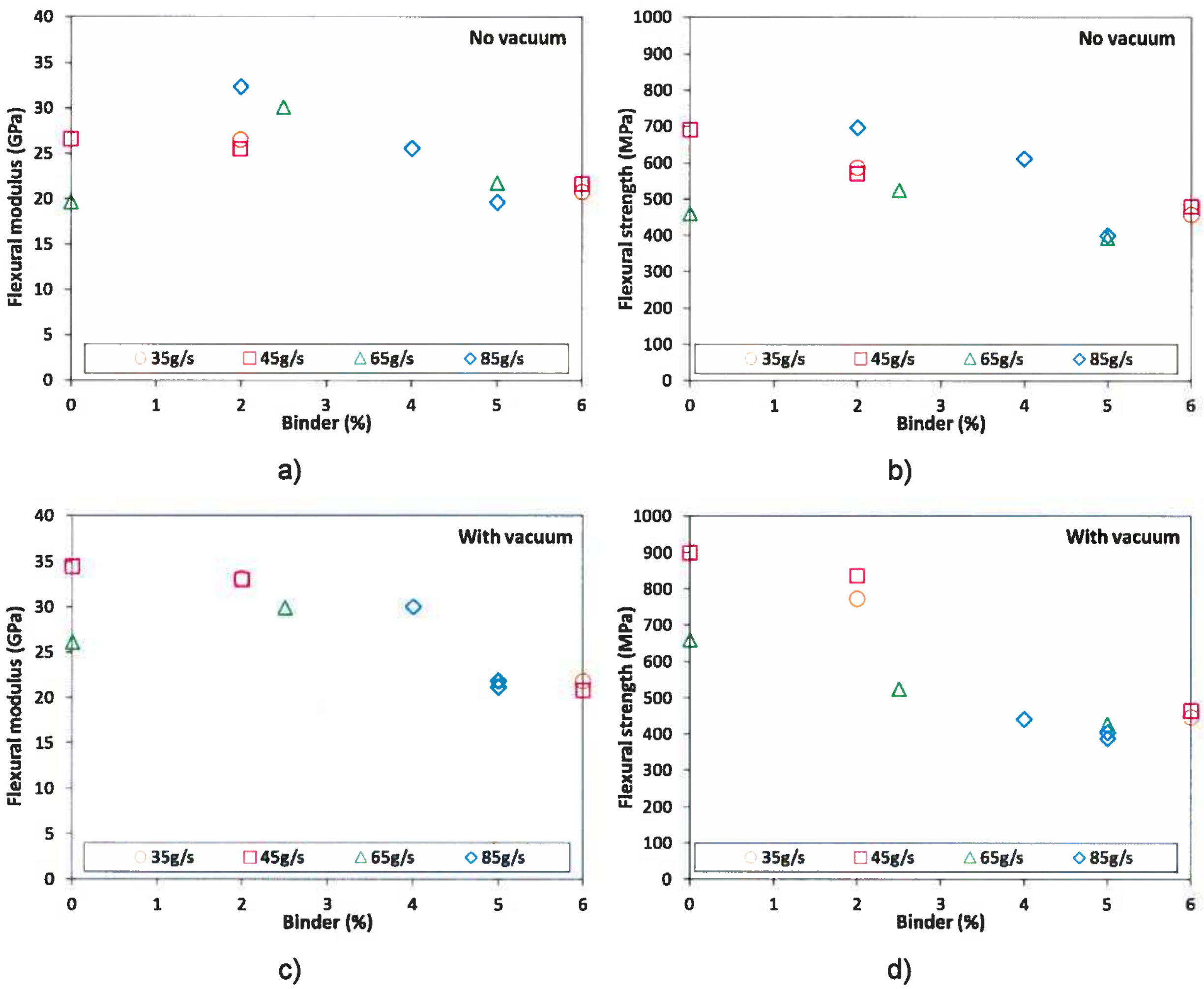
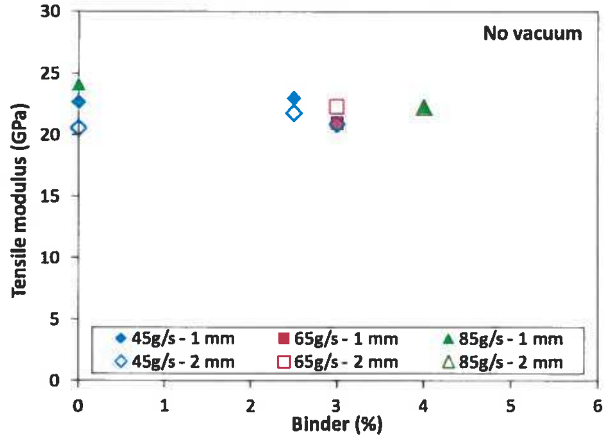
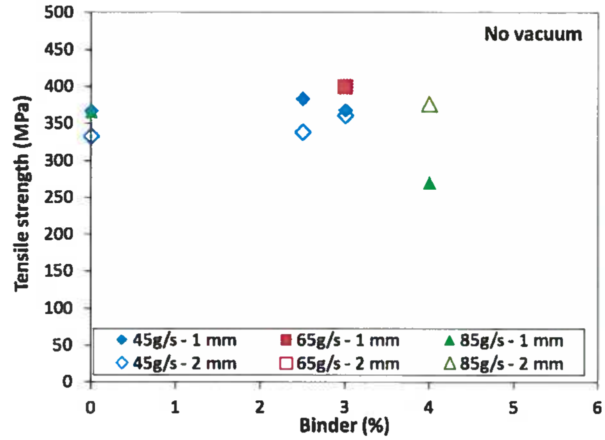


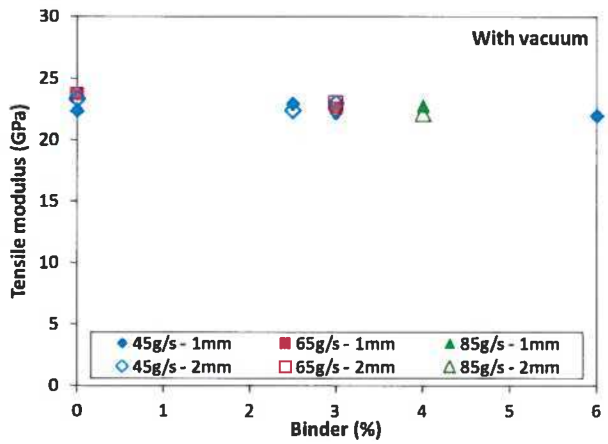
Figure 4: Glass/epoxy composite flexural modulus and flexural strength made by injection HP-RTM under various process conditions



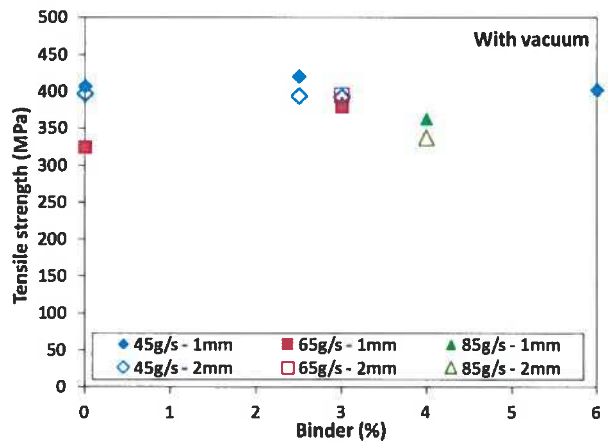
a)



b)



c)



d)

Figure 6: Glass/epoxy composite tensile modulus and tensile strength made by compression HP-RTM under various process conditions

Flexural tests

The flexural properties of glass/epoxy composite panels manufactured by compression HP-RTM are presented in Figure 7. Similarly to the tensile properties, no influence of the binder, the resin injection rate or the gap size was noted for the panel manufactured with compression HP-RTM. However, the use of vacuum assistance reduces the scatter in property for a given condition and overall increases the flexural modulus and flexural strength by 15%.

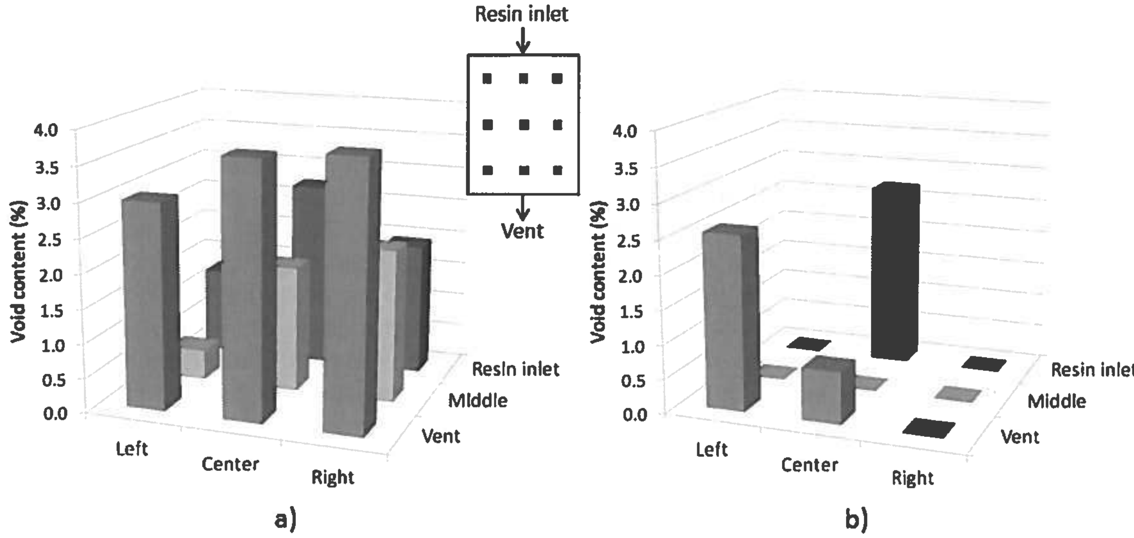


Figure 8: Void content distribution of a composite plaques made by injection HP-RTM (45 g/s, 6% binder), a) without vacuum, b) with vacuum assistance

Discussion

Good quality large glass fibre reinforced epoxy composite panels were obtained with a highly reactive resin. This shows that the 50 second resin process window is sufficient to well impregnate the reinforcement. As the fabric impregnation does not seem to be an issue, the process cycle could be further reduced from 5 minutes to 3 - 4 minutes, still allowing the resin to cure at more than 95%. From the different HP-RTM process parameters tested, the binder concentration is the parameter affecting the most the mechanical performance of the manufactured composite plaques. The effect of binders and tackifiers on the mechanical properties of composite was investigated by other researchers and a reduction of the flexural properties, interlaminar strength and fracture toughness was often reported [20-24]. In particular, Shih and Lee [22] determined that the binder location in the fabric had a strong influence on the fabric permeability and thus the resulting mechanical properties. They found that binder located outside the tow can block the resin flow and decreasing the size of the empty channel between the tows and therefore reduces the permeability. On the other hand, binder located inside the tow helps the fabric permeability but also lead to an increase in void content which is detrimental for the mechanical properties. From the results obtained in this study, it can be assumed that for injection HP-RTM, low binder concentration does not affect the permeability of the quadraxial fabric and a good fabric impregnation is obtained. At higher binder concentration, it can be assumed that the binder starts to affect the fabric permeability and the fabric impregnation, creating void content and lower mechanical properties. In the case of the compression HP-RTM, the binder does not affect the resin flow, as the resin mainly flows through the thickness of the fabric. From the results of this study, low binder concentration on both sides of the fabric, vacuum assistance and medium resin flow rate appeared to be the most favorable parameters to make glass fabric reinforced epoxy composites by injection or compression HP-RTM. Compression HP-RTM seems to be a more versatile process as the composite performances were not affected by any tested process parameters. This might be suitable for the manufacturing of complex tri-dimensional geometry where high binder concentration is needed.

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