Development of innovative flow visualisation methods to investigate the stages of Wet Compression Moulding (WCM) process

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Abstract. The WCM is a novel production technique for fibre-reinforced polymer components. This technique is increasingly adopted in industry, typically in the automotive sector for medium to large-scale production. This process reduces the cost per part significantly by reducing the number of tools and processing steps, relative to Resin Transfer Moulding. To date, the processing variables, their relations and effect on the composite quality have been established through the knowledge gained by technologists. The drive of this research is to develop a fundamental understanding of the impact of process parameters (key process timings and cavity thicknesses, mould closing speed, edge clamping frame dimensions) and material properties (fibre reinforcement compaction response, permeability, and wettability together with test fluid viscosity and surface tension) on textile wetting, impregnation, and resulting composite part quality. In this study, a 480g/m² non-crimp unidirectional glass fibre reinforcement has been chosen and characterised for compaction response, in-plane, and through-thickness permeability. For ease of handling, motor oil (DTE heavy VG100) has been characterised and used as a test fluid. Two experimental flow visualisation setups have been developed at the CACM to investigate the influence of process and material parameters on initial resin application and textile wetting, and the subsequent compression flow stage.

1. Introduction
Fibre-reinforced polymer composites (FRPC) are multifaceted materials, utilising a range of ingredients and more of anisotropic properties. Due to excellent specific strength and stiffness, they are being employed in increasing volume in the high-performance sectors, such as the aerospace, automotive, and marine industries[1]. A diversity of Liquid Composite Manufacturing processes has been established to encounter the necessities of different industry segments, and are distinguished by the construction of the mould and the method used to infuse resin through the preform. Multifaceted FRP parts can be manufactured using the Resin Transfer Moulding (RTM), Compression RTM, and Resin Infusion processes. However, these processes are dependent on the production of a fibre preform, which incurs significant cost within a process chain[2].
1.1. Wet compression Moulding process

Recent progressions in the automotive industry, predominantly by the BMW Group, have seen the introduction of the Wet Compression Moulding (WCM) process that eliminates the prerequisite of preforming. The WCM process is progressively functional in industry, typically in the automotive sector for high volume production of composites. The WCM process reduces cycle time by parallelisation of the process steps such as draping, infiltration and curing [2,3]. This process significantly lowers the cost per part by reducing the number of tool and processing steps. To date, the processing parameters have been established through experience gained by technologists [3,4,5]. The stimulus of this research is to progress with the fundamental understanding of the impact of process and material parameters, on composite quality. As the WCM process is in a relatively early stage of development, no comprehensive numerical/simulation models are available[2-4].

1.2. Material characterisation

An initial experimental study is presented to relate material properties with flow behaviour, ultimately guiding process design in the longer term. A preliminary study was carried out to understand the critical stages of the WCM process, the essential process parameters to design process guidelines. By establishing process design guidelines based on fundamental processing science, the value of the WCM process can be assessed for small and medium-sized companies. This will be carried out by characterising the fibre reinforcement for compaction response, permeability, and wettability followed by characterisation of the resin system for viscosity, surface tension, and degree of cure with temperature.

1.3. Flow visualisation studies

Flow visualisation and lightbox setups have been designed and developed at CACM to investigate the effect of WCM process variables. The flow visualisation setup has been developed to study the WCM process allowing tracking of fluid progression during resin application, mould closure and post-filling. Additionally, provision for the measurement of local fluid pressures within the mould has been made by mounting sensors on the top platen. In future, a method will be developed to locate the voids and air entrapment in the sample images recorded with the flow visualisation setup. The lightbox setup has been designed to investigate the influence of test fluid viscosity, gravity and capillary driven flow[8] and surface tension on textile wetting.

2. WCM Process Description

Figure 1 illustrates the WCM process, which comprises of creating 2D stack from textile reinforcing materials, followed by pouring of the required volume of resin over the upper stack surface. The stack is then transferred into a heated mould mounted in a press, to perform a simultaneous draping and infiltration process, before resin cure[1,5]. The quality of the final part produced by WCM depends on the following critical process factors: stack mass and storage time, resin volume, component and tool temperature, resin infiltration period, and compaction load[3,4]. This study will investigate the influence of stacking sequence, test fluid viscosity and surface tension in more detail. Due to the complexity of the draping process, the current focus is on the resin application and infiltration processes in this study.

3. Material Characterisation

To study the WCM process, and material parameters, an 480g/m² non-crimp Unidirectional (UD) E-glass reinforcement (UE480 by Colan) has been used in this article. A comprehensive programme is presented to evaluate the 2D in-plane and 1D through-thickness permeability behaviour using facilities developed at CACM [10]. The experimental plan includes three different layups, created by varying stacking sequence, as shown in table 1. For ease handling, motor oil DTE heavy medium VG68, DTE light VG32, Alpha SP220 by
Mobil have been used for flow visualisation studies. Using motor oils gives a range of options to study the influence of viscosity and surface tension of test fluid that can be tailored for each process necessity. The viscosity of test fluid has been measured using a Brookfield viscometer (Cup and Bob type). The viscosity of the test fluids used are shown in figure 8(a).

Table 1. Definition of the sample stacking sequence patterns.

| Layup          | Stacking Sequence |
|----------------|-------------------|
| Unidirectional | 0°UD [0°/0°/0°/0°/0°/0°/0°/0°/0°/0°] |
| Bi-directional | LU1 [0°/90°/0°/90°/0°/90°/0°/90°/0°/90°] |

4. Experimental Facility

4.1 Flow Visualisation Setup
An experimental setup is needed to investigate the influence of process parameters throughout the resin application, draping, infiltration, and curing stages of WCM process. A facility was designed and built to monitor the wetting, resin flow and void/bubble movement, together with measuring local resin pressures, and the total required mould force. Figure 2 displays a graphic of the facility mounted in an Instron 1186 universal testing machine (UTM). The UTM provides precise control of mould closure, which is essential to achieve the required fibre volume fraction and part thickness, while the load cell in the Instron enables measurement of total applied force. The setup comprises of two platens, the lower platen is made of glass, allowing visual monitoring of test fluid and air bubble flow, and is of 350 mm square and 55 mm thick [7,8]. The upper platen is designed in such a way to illuminate the stack from the upper side, using an internal lighting arrangement.

Additionally, provision for measuring local fluid pressures at five positions within the mould has been made by mounting pressure transducers in the top platen. The sample saturation and flow front progression are monitored using an Epix digital camera[7,8]. Images are captured using a mirror fixed at 45° from the horizontal axis. A sequence of images captured during the flow front progression of a 0°UD stack is shown in figure 3. These images illustrate the unsaturated, saturating, and saturated regions in a single layer sample during compaction.

4.2 Lightbox Setup
An experimental facility is required to study the influence of test fluid properties on the wetting phase of WCM process. A setup was developed to observe the impact of reinforcement architecture, stacking sequence, test fluid viscosity and surface tension, and hold time on the wetting phase. The facility includes a lightbox which has translucent top and opaque sides powered by fluorescent lights. The translucent top surface allows even dispersion of light enabling visual monitoring of the flow front through a textile sample two epix (EPIX PIXCI S14) cameras are used to monitor the flow front from top and side views. The representation of the facility is given in figure 4. The influence of test fluid
viscosity on the wetting of fibre reinforcement has been studied with three layers of 0°UD stack of size 270 x 270 mm. The images are captured at an interval of one frames/sec for ten minutes from the start of each test and the images are processed using ImageJ software. The images captured using the facility at 90th second of a trial with different viscosity test fluids are shown in figure 7.

![Figure 2. Schematic of flow visualisation setup.](image)

**Figure 2.** Schematic of flow visualisation setup.

![Figure 3. Flow front progression of layup LU1 Captured using flow visualisation setup. Flow fronts are presented the following times after initiation of mould closing: (a) 1 s, (b) 81 s, (c) 85 s, (d) 120 s.](image)

**Figure 3.** Flow front progression of layup LU1 Captured using flow visualisation setup. Flow fronts are presented the following times after initiation of mould closing: (a) 1 s, (b) 81 s, (c) 85 s, (d) 120 s.

5. **Result and Discussion**

5.1. **Permeability studies**

A 2D in-plane permeability studies were done by radial flow, constant pot pressure, discreet and transient flow method [7,9]. The flow front evolution recorded during permeability measurement is shown in figure 6(a) and 6(b), measured average permeability values in both principal directions for the 0°UD, and LU1 stacks are shown in figure 5(a) and (b). Flow front progression pattern for 0°UD stacks are elliptical with the major axis oriented in the direction of 0° plies, this confirms the fact that
these layups are isotropic as shown in figure 6(a), whereas the layup LU1 flow front is about circular as shown in figure 6(b) and shows anisotropic material behaviour. For both layups, as expected, the permeability value decreases with an increase in fibre volume fraction due to shrinkage of the flow path and an increase in resistance to fluid flow.

![Figure 4. Schematic of lightbox setup.](image)

Through-thickness permeability studies were carried out by saturated flow, steady-state, permitting numerous fibre volume fractions measurements from a single sample [10]. The results of the measurements are shown in figure 5(c). The permeability of 0ºUD layup is lower than that of LU1 due to nesting effect. As expected, the permeability value declines with an increase in fibre volume fraction for both layups.

![Figure 5. Permeability data for 0˚UD and LU1 stack layups (a)K_{11}, (b)K_{22}, and (c)K_{33}.](image)
5.2. Flow visualisation studies
A parametric study was conducted using the flow visualisation set up to study the influence of reinforcement stacking sequence, measure and correlate the localised fluid pressure with permeability data. Localised fluid pressure data recorded during one experiment with each stack type is shown in figure 6(d) and (e). The presented data indicates that there is a notable change in local fluid pressure distribution among the two layups. A remarkable observation has been made with the pressure traces in the sensor at P5 with both the 0˚UD and LU1 layups, as shown in figure 6(d) and (e). For the isotropic LU1 layup, equal pressures are noted between the pressure transducer sets (P2 and P4, P1 and P5) mounted at an equidistance of 37.5 mm from tool centre as shown in figure 6 (c). For the 0˚UD layup, a significant variation is noted between the P1 and P5 transducers, due to lower stream resistance shown through the stack in the warp direction. The pressure distributions pattern aligns with the flow front progression pattern recorded during the in-plane permeability measurements, and the measured anisotropy ratios for each layup type.

![Flow front for stack layups](image)

Figure 6. Flow front for stack layups (a) 0˚UD and (b) LU1, Transducer coordinates (c), and Pressure plot for stack layups(d) 0˚UD and (e) LU1.

5.3. Lightbox setup study
In-plane flow front progression for test fluid of varying viscosity at 90th second of the test is shown in figure 7. The reinforcement warp and weft direction are marked as Y and X as shown in figure 7(d). It is observed that the highest viscous test fluid (SP220) has the least propagated and remained as a pool on top of the stack, as shown in figure 7(a). As expected, the flow front progression is higher along warp direction as shown in figure 8(b). The above trend confirms that initial wetting is driven by gravity and capillary forces[13]. Additionally, the lowest viscous test fluid (VG32) has propagated the...
most in both warp and weft direction and confirming that viscosity of test fluid is influential in the wetting process.

![Figure 7](image-url) **Figure 7.** Top and front view of flow front progression for test fluids (a) SP220, (b) DTE Heavy VG100, (c) DTE Heavy Medium VG68, and (d) DTE light VG32.

![Flow Front Progression](image-url) **Figure 8.** (a) Viscosity of test fluids and (b) Test fluids flow front progression

### 6. Concluding Remarks

A preliminary parametric study of the WCM process has been presented, focusing on the resin application and mould closing phases of the process. A unidirectional glass fibre reinforcement has been characterised for permeability by relating three different stack sequence. Different motor oils are characterised and used as a test fluid. A purpose-built flow visualisation setup has been developed to monitor fluid flow front during resin application, mould closure, and post-filling phases, including measurement of local fluid pressures and total mould clamping force. When correlating the flow visualisation and permeability studies, the results align together. A lightbox setup has been developed to monitor the wetting phase of WCM. Using the lightbox setup, a study has demonstrated that test fluid viscosity influences the wetting stage. Future research is focused on investigating the influence of test fluid surface tension on the wetting process, the impact of hold time, and edge clamping, as well as the manufacture of real panels. Models (analytical and numerical) will be established to comprehend the effect of process parameters and material properties at different stages of WCM, working from the observations of flow visualisation and real part manufacturing studies.
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7. References
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